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ELECTRICAL CIRCUITS AND MACHINERY

WORKS OF
PROFESSOR J. H. MORECROFT

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ELECTRICAL CIRCUITS AND MACHINERY

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AND
FREDERICK W. HEHRE
Associate Professor of Electrical Engineering, Columbia University

VOLUME III

EXPERIMENTS

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PREFACE

THIS brief course of experiments has been found suitable for technical students specializing in other branches than Electrical Engineering. The experimental work here outlined presupposes a good course in experimental Physics, covering all ordinary work in electrical measurements. Such a course is generally given to the engineering student in his second year, and the experiments here outlined are suitable for third- and fourth-year students.

The scope of the experiments is sufficiently wide to acquaint the student with all the principal types of electrical machinery, and the schemes of testing suggested are designed to bring out the characteristics that are most important to the operating engineer. Each experiment can be performed in one laboratory period of three or four hours, so that the entire work outlined in this text can be covered in a one-year course of one laboratory period a week. This seems to be the amount of time generally allotted for work of this kind in the schedule of the non-electrical student.

It will always be found advisable to have one classroom period, as well as one laboratory period, per week, so that the class may have a general discussion of the significance of the experimental work before attempting to carry out the tests in the laboratory.

J. H. M.
F. W. H.

JUNE 1, 1925.

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CONTINUOUS-CURRENT EXPERIMENTS

CONTINUOUS-CURRENT EXPERIMENTS

I. APPLICATIONS OF OHM'S LAW

Object.—Measuring drop of potential along a conductor. Variation of resistance with temperature. Measurement of resistance of circuits of a generator or motor.

Theory Involved.—The resistance of a conductor being proportional to its length, it follows that the potential difference between two points in such a conductor, when carrying current, must be exactly proportional to the distance between them. As the resistance of a conductor depends upon the material used, we may expect the drop of potential per unit length along one conductor to be different from that along another, even though both conductors are of the same cross-section and are carrying the same current. Also, by Ohm's law, we expect the drop per unit length to be proportional to the current.

Some materials increase their resistance with rise in temperature and others have a fall in resistance as the temperature is raised; as the temperature of a conductor increases with increase of current we may expect the resistance to vary with current. This may well be shown by measuring the resistance of an incandescent lamp, first with very small current and then with current sufficiently large to bring the lamp to normal brilliancy. A metal filament lamp may increase its resistance many times from its cold to its hot condition, while a carbon filament (not metallized) lamp shows a decrease under the same conditions.

The easiest and most convenient method of measuring resistance in the ordinary laboratory is by means of an ammeter and voltmeter; the resistance is equal to the quotient of the volts impressed on a circuit, by the current flowing through it. In using this method of measurement, certain precautions must be taken if damage to meters and machines is not to result. Some circuits have very low resistance, so low that if they were to be connected across the electric supply line, such a large current would flow as to constitute a short circuit. Thus, an armature might have a resistance of 0.01 ohm; if this were connected directly across a 110-volt supply line, a current of 11,000 amperes would flow, if the pressure of 110 volts was maintained. Actually it would not be, because of excessive line drop, so that something less than this current would flow.

In order to limit the current flowing through a circuit, it is advisable to use a rheostat or bank of lamps in series with it, before connecting to the supply line. The current is then limited by this additional resistance, if the resistance of the circuit itself is not sufficient to do so.

A further precaution to be observed, in measuring the resistance of inductive circuits, has to do with damaging the voltmeter by the effect of self-induction. If a highly inductive circuit, such as the field circuit of a generator, is connected to a 110-volt supply, and then the switch connecting it to the line is suddenly opened, the e.m.f. of self-induction will be very high; it might go to 1000 volts or more. If at this time there should be a voltmeter connected across the field coils, it would probably be ruined by the excessive voltage. The precaution to be taken in such a case is *to always disconnect the voltmeter from across an inductive circuit before opening the supply switch.*

If a voltmeter or ammeter is connected in a circuit, by the theory of probability it will be connected in backwards, half of the times, so as to give reversed deflection. In such a case the connections of the meters must be reversed. In the case of an ammeter with internal shunt, the circuit should be opened before reversing the ammeter connections, as severe burns may otherwise result from the arc which will form at the point where the circuit is opened. In case an outside shunt is used, the leads connecting the meter to the shunt should be reversed; it makes no material difference whether they are reversed at the meter or at the shunt, but to cultivate safe habits it is better to reverse them at the shunt.

A voltmeter is connected directly across the line and if it is connected in backwards *its connecting leads must be reversed at the line, not at the meter.* If the student tries to reverse them at the meter, he is likely to be badly burned by the short circuit which may easily result. If the leads are left connected to the line and taken off the voltmeter, the student will have in his hands the two ends of a power supply with probably hundreds of kilowatts power capacity. If the ends which have been taken from the voltmeter happen to come together, the line will be short-circuited at this point and a very bad arc will result and severe damage may be done. *Always leave the leads connected to the voltmeter and reverse them where they connect to the line;* in this way no harm can occur.

In measuring the resistance of the circuits of a machine, it is to be remembered that, the armature inductors being always of copper, their resistance will be independent of the current except for heating. The same applies to the machine leads, the resistance of which is very small. The brush contact resistance is the resistance of the surface contact between the carbon brushes and the commutator. This resistance is quite appreciable and decreases with increase of current strength; it decreases as the mechanical pressure between the brush and the commutator increases. The resistance of the brushes themselves is insignificant.

Procedure.—It is convenient to have a board with four pieces of wire of the same cross-section mounted upon it (all connected in series) from 36 to 48 inches long, one each of iron, copper, aluminum and German silver. Connect the wire board to the power supply through a lamp board and suitable variable resistance as shown in Fig. 1. Obtain (from the instructor) the safe current-carrying capacity of the German-silver wire; be sure that the ammeter and variable resistance will safely carry this value of current. The voltmeter to be used should have a capacity on one range of about 15 volts with another range of 3 volts or lower.

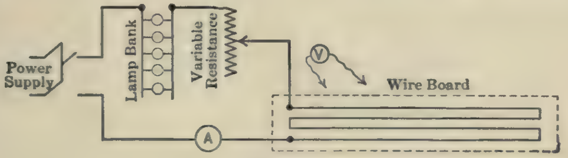


FIG. 1.

With a sufficient number of lamps in the lamp bank, change the current, by varying the resistance in the variable rheostat, until exactly one-fifth of the safe current value for the German silver is flowing. Then, using the maximum range on the voltmeter, connect one of its leads to one end of the copper wire and the other lead to the wire at the 6-inch mark. If the reading is within the next lower range, try this one.

With the current continually maintained constant, take a set of readings for increasing lengths of the copper wire, each length being 6 inches greater than the previous one, until the entire length of the copper wire has been included; do the same for the remaining three wires. Raise the current to three-fifths and finally to the full value of the current the German-silver wire will carry, each time measuring the fall in potential along each wire.

Calculate the resistance of each wire and the amount of power used in each wire, at each value of current. Determine the average value of the resistance per mil-foot for each material, and with the value obtained, calculate the resistance of 1000 feet of No. 10 B. & S. gage wire.

Determine the hot and cold resistance and the total watts for a carbon lamp and for a Mazda or tungsten lamp, each of about 50 watts rating. To determine the hot resistance of the lamps, connect each of them in turn to a source of e.m.f. of about 115 volts, in series with an ammeter of about 2 amperes range, as in Fig. 2. No series resistance is necessary, as the lamps themselves are of high enough resistance and are intended to withstand the full line voltage. Determine the voltage and current of the lamp while incandescent. The voltmeter used should have a range of about 150 volts, and be so connected that the ammeter does not register the voltmeter current.

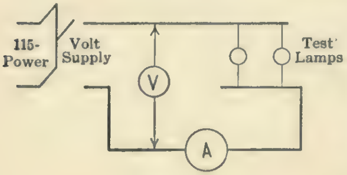


FIG. 2.

Determine the cold resistance of the lamps by means of a Wheatstone bridge.

Before making tests on the machine circuits, determine the full-load armature current of the machine, the armature-circuit resistance of which is to be measured, from its name-plate data. Connect the armature circuit in series with an ammeter, a lamp bank and a variable resistance, all of suitable current-carrying capacity, as shown in Fig. 3.

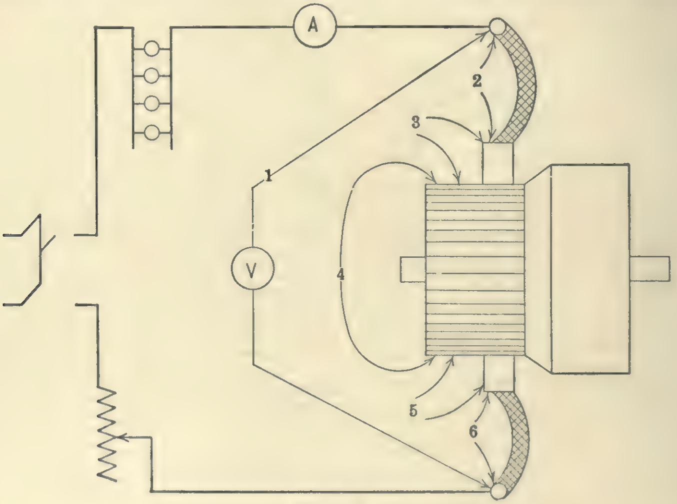


FIG. 3.

Close the line switch and adjust the current to one-third of the full-load rated value of the machine. Using first the highest range upon the voltmeter, attach the voltmeter leads to the two terminals of the machine (position 1 in Fig. 3). If the reading is within the next lower range on the voltmeter, remove the leads *from the machine terminals* and shift to the desired range. With a deflection on the voltmeter as large as obtainable, read ammeter and voltmeter simultaneously and record the readings in a log as in the accompanying table.

Amperes	Volts Drop							Difference between 1 and 7
	1	2	3	4	5	6	7	
	Across Entire Armature Circuit	Across Ends of One Machine Lead	Across One Brush Contact	Across Armature	Across Second Brush Contact	Across Ends of Second Machine Lead	Sum of Drops 2, 3, 4, 5, and 6	

From the readings taken with the voltmeter connected across the machine terminals (position 1), the resistance of the entire armature circuit can be calculated. Leaving one of the voltmeter leads upon one of the machine terminals, trace the cable leading from the terminal used, to one of the brushes of the machine and attach the other voltmeter lead to the brush pig-tail, or other convenient place (position 2). From this voltmeter reading the resistance of one of the machine leads is determined. Then shift the voltmeter leads successively to positions 3, 4, 5, and 6, and continually maintaining the current constant, read the meters as before. These readings must be taken as rapidly as possible, so that the armature circuit shall not heat up and hence change its resistance, while a set of readings are being taken. The sum of readings 2, 3, 4, 5 and 6, entered in column 7 of the log, should equal the values in column 1, the measured drop across the entire circuit.

Repeat the operation indicated, using two-thirds and full-load armature current, respectively. Calculate the values of resistance and tabulate in a form similar to the table given above.

If the generator being tested is equipped with a commutating-field winding (in series with the armature), its resistance may also be determined, an extra column being provided in the log.

Caution.—Great caution must be exercised in obtaining the voltage readings across the various parts. If large readings upon the voltmeter are desired, it will be necessary to shift from one low range to another; *it must constantly be borne in mind that a voltmeter needle is easily bent or the instrument entirely burnt out, if a high voltage is applied to a low-range connection.*

In determining brush drop, attach one voltmeter lead to the brush pig-tail used in determining the drop across the machine leads, and hold the other voltmeter lead on the commutator bar directly under the brush; be careful not to touch the terminal of the second voltmeter lead against the brushes. To determine the drop across the armature winding, hold the terminals of the voltmeter on commutator bars which are under brushes of opposite polarity; do not touch the terminals, which are held on the commutator, against the brushes while reading the voltmeter.

With the higher values of current through the armature, the armature may begin to rotate. Do not permit it to do so, as it will generate a counter e.m.f. which will decrease the current and cause an apparent increase in the armature-circuit resistance. Use a brake or equivalent device to hold it stationary, if necessary.

With the higher values of current through the armature, it may be convenient to remove the adjustable resistance from its position in Fig. 3, and place it in parallel with the lamp board.

Connect the shunt field, the resistance of which is to be measured, in series with an ammeter of suitable capacity, to a source of voltage equal to that for which the field was designed, as indicated in Fig. 4. Using a voltmeter of suitable range, determine the difference of potential between the ends of the field and at the same time read the current on the ammeter. *Before opening the field circuit be sure the voltmeter is disconnected at the field terminals;* when opening the field switch, do so slowly, drawing out the arc.

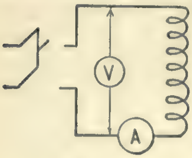


Fig. 4.

Next determine the resistance of the shunt field, using a Wheatstone bridge.

Curves.—Plot the readings obtained for each wire on a separate sheet of cross-section paper, using one set of co-ordinates. Plot voltmeter readings as ordinates and lengths as abscissae.

Questions.—

1. How does drop in potential vary along a conductor carrying current?

2. Why are the curves straight lines?

3. Why did the wires expand during the test?

4. Which metal is the best conductor?

5. Which is best suited for use as resistance in rheostats, and why?

6. How do the values obtained for resistance per mil-foot and for the resistance for 1000 feet of No. 10 B. & S. wire compare with values in the wire tables?

7. Explain the difference in the hot and cold resistances in the lamps tested.

8. Explain the principle and operation of the Wheatstone bridge.

9. In determining the resistance of the lamps, what would the ammeter have read if the voltmeter had been connected directly across the lamps, instead of as shown in Fig. 2, and both meters were read simultaneously (consider the resistance of the voltmeter as 100 ohms per volt of range)?

10. Explain why armature and commutating-field resistances are made as low as they are.

11. How do the resistances of the various parts of the armature circuit vary with current?

12. Why cannot the resistance of an armature circuit be accurately determined with the ordinary Wheatstone bridge?

13. Why should an inductive circuit never be opened if a voltmeter is connected across any portion of it?

II. THE SHUNT GENERATOR

Object.—Preliminary work with a shunt generator. Obtaining magnetization curve and external characteristic of the shunt generator.

Theory Involved.—The student is first to familiarize himself with the component parts of the machine to which he has been assigned, and to look over their construction and relation to one another, in order to get a general idea of the generator; he should also satisfy himself that the machine is in proper condition to be operated.

The magnetization curve, showing the relation between generated voltage of the armature and field current, and plotted between these quantities, really constitutes a B–H curve for the magnetic circuit of the machine, if the speed is held constant while the data are obtained. The voltage generated in the armature is evidently proportional to the flux density and, as the magnetizing force, H, is proportional to the current sent through the field winding, the truth of the above statement is evident.

The knee, or saturation point, of the B–H curve of a machine is by no means as marked as that given in the magnetization curves for iron and steel in Section 52, Volume I. This is because most of the reluctance of the machine's magnetic circuit is in the air gap, and the magnetization curve for air is a straight line.

The external characteristic of the shunt generator shows the variation of terminal voltage as the load current is varied, the speed being constant and the field circuit resistance being kept fixed at that value which gives rated terminal voltage at rated full-load current. With increasing load the terminal voltage of a shunt generator falls, owing to three causes: IR drop in the armature, armature demagnetizing effect, and decrease of shunt-field current.

As a shunt generator is self-excited, it is necessary that there be some residual magnetism to start the building-up process. Also the field-circuit resistance must be sufficiently low, and the field connected to the armature in proper order or polarity. These points are analyzed in the text in Sections 220 and 221, Volume I.

Procedure.—From inspection of the machine, and consultation with the instructor, obtain data for filling out the following form:

General

Type of generator. . .shunt or compound

Kw. output. . . . .

Rated voltage. . . . .

Rated current. . . . .

Rated speed. . . . .

Fields

Number of main poles. . . . .

Main pole arc in degrees. . . . .

Main pole width. . . . .

Main pole length. . . . .

Main pole breadth. . . . .

Number of shunt-field turns per pole. .

Number of series-field turns per pole. .

Number of commutating poles. . . . .

Commutating pole arc in degrees. . . . . .

Commutating pole width. . . . .

Commutating pole length. . . . .

Commutating pole breadth. . . . .

Number of commutating-field turns per pole. . . . .

Armature

Type. . . . . .ring or drum

Winding. . . . . .series or multiple

Circumference. . . . .

Peripheral speed in ft. per min. . . . .

Number of slots. . . . .

Active length. . . . .

Number of coils. . . . .

Conductors per coil. . . . .

Total number of conductors. . . . .

Conductors per slot. . . . .

Commutator

Circumference. . . . .

Peripheral speed in ft. per min. . . . .

Active length. . . . .

Total length. . . . .

Total number of bars. . . . .

Width of bars. . . . .

Width of insulation. . . . .

Number of bars between brushes of opposite polarity. . . . .

Average voltage between bars. . . . .

Kind of brushes. . . . .

Brush area per set. . . . .

Current density in brushes, in amperes per sq. in. . . . .

In getting the magnetization curve of a shunt generator, it is treated as a separately excited machine; the field current is obtained from some outside source of power and varied from zero to a value which saturates the iron of the magnetic circuit. In order to do this it is most economical of apparatus to use a potentiometer connection of the field circuit to the source of power. Instead of connecting a variable resistance in series with the field coils, the variable resistance is connected directly across the power supply which is to excite the field, and the field circuit is then connected to one end of the resistance and the sliding contact as in Fig. 5. By this connection the field current may be varied from maximum value to zero with only one rheostat. If the wire of the rheostat is tapered, the field circuit is to be connected across the *finer* wire.

Record in the log the resistance of the rheostat used as potentiometer.

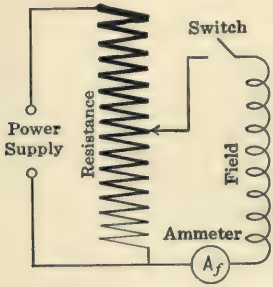


FIG. 5.

With the generator running at rated speed and with the field connected as in Fig. 5, set the brushes in the proper neutral position (consult instructor about this). With a voltmeter connected across the armature, read the generated voltage with zero current in the field circuit; this is obtained by putting the sliding contact of the potentiometer (Fig. 5) down to the bottom.

Then take a series of readings between field current and generated voltage (speed continually held at constant value) in about eight equal steps up to 50 per cent above the rated voltage of the machine. In getting this " going-up " magnetization curve always adjust to the desired field current by *increasing*, not decreasing, the current. If more than the desired current has been obtained by improper adjustment of the potentiometer, adjust for the desired value, then open the field circuit slowly, leave it open for a second, then close it and take a reading.

After reaching the 50 per cent above rated voltage point, get a " coming-down " magnetization curve with about the same number of points, now always approaching a desired point with *decreasing* field current.

In getting the external characteristic, it is first necessary to make the machine " build-up," self-excited. The connections are made as in Fig. 6. With switches S_1 and S_2 open, and the machine running at rated speed, note the reading of the voltmeter. With all the field rheostat resistance in, close S_1 and note whether the voltmeter reading increases or decreases. If it increases, the field is connected to the armature with proper polarity; if it decreases, reverse the connections of the field circuit to the armature circuit.

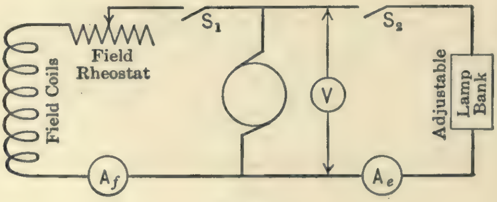


FIG. 6.

When the field has been properly connected to the armature, gradually decrease the resistance of the field rheostat and notice the reading of the voltmeter. This will be seen to rise very slowly at first until a critical adjustment has been reached, then build up rapidly, with no further change in the field rheostat, until quite high voltage (perhaps greater than rated voltage) is being generated.

With the voltage at about the rated value and a few lamps connected in the lamp bank, close the switch S_2 and adjust the load resistance to get nearly rated current. Then by a series of adjustments get rated full-load current flowing in the load circuit, with rated voltage across the armature. This requires adjustment of both load resistance and field rheostat. (Be sure speed is kept at rated value.)

With this adjustment of the field rheostat, get a series of readings between load current, field current and terminal voltage, for loads greater and less than rated value. Get one for zero load current and about seven other points up to 50 per cent overload. From this curve the regulation of the machine is obtained.

Obtain a similar series of readings after having adjusted the field current to give rated voltage at *no load*. In this case (particularly if the machine being tested is not equipped with commutating poles) the curve may be continued, by gradually decreasing the resistance of the load circuit, until the load is finally short-circuited. This series of readings will yield a curve of the form shown in Fig. 250, Volume I, the reasons for the form being discussed there.

In the last two tests the resistance of the shunt-field circuit should remain essentially constant during the two runs. Whether or not it did so may be shown by calculating its value for each load from the readings of the field-current ammeter and voltmeter across the terminals. If, as frequently happens, the field-circuit resistance gradually increases as the tests are carried out, it shows that the field had not sufficiently warmed up while the magnetization curve was being obtained, and so has kept increasing its temperature, and hence resistance, during the progress of the tests.

If the machine used in the previous tests is not equipped with commutating poles, bring the machine to rated voltage, at rated speed, with no load upon it, and adjust the position of the brushes to give best commutation, as indicated by minimum sparking. Then add full load and shift the brushes forward until the point of best commutation is again reached; note any change in the voltmeter reading while this is being done. Then shift the brushes further forwards and then backwards beyond the no-load neutral point, again noting the voltmeter and sparking after each shift.

Disconnect the field circuit from the armature, and using a suitable resistance to control the current used, measure the resistance of the armature circuit for about six values of current, from 50 per cent overload current down to one-quarter load current. The voltmeter used for measuring the voltage in this test should be connected to the same terminals to which the voltmeter was connected when getting the external characteristic.

Curves.—On the same sheet plot the magnetization curve, for both increasing and decreasing field current, the external characteristics for both adjustments, and the armature-circuit resistance-drop curve. For these curves use volts as ordinates. Use different scales for field current and load current; on the average machine a ratio of scales of ten to one is suitable. Indicate by a vertical dashed line the value of full-load rated current, and by a horizontal dashed line the value of rated terminal voltage.

Questions.—

1. If the rheostat used as potentiometer is tapered, why should the field be connected in parallel with the finer wire, rather than across the coarser wire?

2. If the rheostat you used as potentiometer in getting the magnetization curve had been used as a series resistance, what variation in field current could have been obtained?

3. How much series resistance would it have been necessary to use, in series with the field, to get the lowest value of field current (other than zero) at which a point on the magnetization curve was obtained?

4. What must be the relative maximum current-carrying capacities of the wire used in the potentiometer and in the series resistance?

5. Why are the ascending and descending magnetization curves different?

6. Which curve should be used in calculating the minimum amount of resistance necessary in the shunt-field rheostat (Fig. 6)? Why?

7. For what reasons might a self-excited generator fail to build up?

8. What is the regulation of the machine you tested, for both external characteristics?

9. Why should the armature resistance of a generator be made low?

10. Why does the armature-circuit resistance show such a large variation as the current through the armature is varied?

11. Why does the voltage of a shunt generator fall as the machine is loaded?

12. Explain the changes in voltmeter reading during the last test, when brushes were shifted.

13. If the flux density in the air gap is 50,000 lines per square inch, what is the flux per pole?

14. What is the actual length of conductor per path in the armature of the machine you tested?

15. Explain why the use of commutating poles eliminates sparking and the necessity of shifting brushes.

III. THE COMPOUND GENERATOR

Object.—Study of the compound generator. The armature characteristic of a shunt generator. External characteristic of a compound generator. Effect of speed variation on the compounding action of the series field.

Theory Involved.—From the previous test it was found that the terminal voltage of a shunt generator falls as load is increased. In general it is desired to keep the voltage constant at some point in the network supplied by the generator, as load is increased, and this evidently requires that the terminal voltage of the generator increase with load and increase sufficiently to just overcome the IR drop in the cables connecting the generator to the feeding point.

With the ordinary shunt generator it is possible to make the terminal voltage remain constant, or even increase, as load is increased, by manual control of the rheostat in series with the shunt field, by cutting out this resistance with increase of load current. The *armature characteristic* of a shunt generator (Fig. 251, Volume I) is the curve showing the relation between the external current and shunt-field current when the terminal voltage is maintained constant by shunt-field regulation, as the load is varied. The curve is generally concave upward (when plotted with shunt-field current as ordinate) because of the fact that the increase in flux per unit increase of the shunt-field current, as indicated by the magnetization curve, decreases as the iron approaches saturation. Accordingly there is needed a greater increase in shunt-field current to compensate for a given value of armature IR drop and armature reaction at high loads than at light loads.

This increase in field strength, which is controlled by shunt-field current in obtaining the armature characteristic of a generator, may be accomplished automatically by using a series-field winding, as explained in Section 224, Volume I. The regulation of voltage by series field is entirely automatic and instantaneous, because the increase in load current, which gives the extra IR drop and armature reaction, is the same current as is used to give increased m.m.f. on the field poles.

If the number of turns in the shunt field is known, the correct number of series turns can at once be calculated, as the ampere-turns of the series field at full load must be the same as the increase in ampere-turns of the shunt field from no load to full load, when getting the armature characteristic. This calculation was indicated in Section 225, Volume I.

A machine which is flat-compounded (same terminal voltage at full load as at no load) will generally be over-compounded at intermediate loads; the external characteristic of a compound generator is always convex upward.

In studying the compound generator it is frequently desirable to express the magnetic effect of the series-field current in terms of the shunt-field current, and so determine the total magnetizing current of the generator in terms of the shunt-field current. If the actual number of turns in each field, as well as the resistances of the series field and of its diverter, are known, it is possible to calculate the ampere-turns of each field for known currents.

If, however, only the ratio of the number of turns in the series field to the number of turns in the shunt field is known, the calculation is simple.

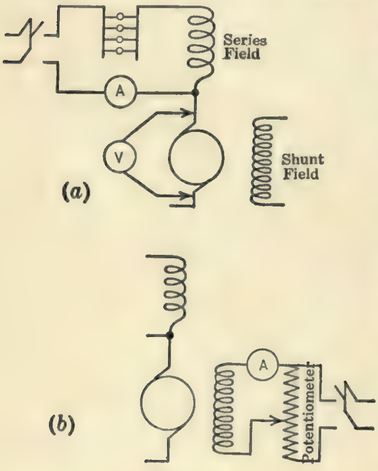


FIG. 7.

To determine this ratio, the series field of the generator is first separately excited from some outside source, the shunt field being open, as in Fig. 7*a*. With a known current through the field, and the generator operating at exactly rated speed, the voltage across the armature is read by voltmeter. The shunt field is then separately excited, the series field being open, as in Fig. 7*b*. With the generator again operating at exactly rated speed, the shunt-field current is gradually raised until the armature voltage is exactly the same as when the series field only was excited, and the shunt-field current read.

Since the armature, in both cases, was turning at the same speed and generated the same voltage, it must have cut the same total flux. We may write then that

$$\phi = \frac{0.4\pi N_1 I_1}{\mathcal{R}} = \frac{0.4\pi N_2 I_2}{\mathcal{R}},$$

where ϕ = the total flux cut;

$\mathcal{R}$ = the reluctance of the machine's magnetic circuit;

N_1 = the number of shunt-field turns;
N_2 = the number of series-field turns;
I_1 = the shunt-field current;
I_2 = the series-field current.

The above expression may be simplified to read

$$\frac{I_1}{I_2} \equiv \frac{N_2}{N_1} = K \quad \text{or} \quad I_1 = I_2 \times \frac{N_2}{N_1} = KI_2,$$

which states that

$$\text{Equivalent shunt-field current} = \text{series-field current} \times \frac{\text{series turns}}{\text{shunt turns}}$$
$$= \text{series-field current} \times K.$$

With a diverter across the series field, the ratio determined is not the true ratio of turns, but an equivalent ratio. The effect of the diverter is to divert some of the external current from the series field, but it may also be considered as a reduction of the total series turns, the turns left carrying the entire external current.

For any load condition of the compound generator we may then determine the total magnetizing effect in terms of the shunt-field current, by adding to the actual shunt-field current the corresponding series-field current multiplied by "K."

If a compound generator has been correctly designed to give flat compounding at its rated speed, it will not do so at other speeds. Thus, if a machine is run, say 20 per cent above rated speed, and is adjusted at no load by its shunt field to give rated voltage, it will be operating on a different part of the magnetization curve than that for which it was designed. In Fig. 8 is shown the magnetization curve of the machine, M being the normal point of operation for no load, at rated speed. The extra ampere-turns given at full load by the series field are shown by AB, giving an increase in the generated voltage of CD, which presumably is just sufficient to overcome the IR drop and armature reaction for full-load current.

If the machine is now operated 20 per cent above rated speed, the required value of shunt-field ampere-turns at no load, to give rated voltage, is given as OA'; the machine operates at a point P of its magnetization curve, such that OC' increased by 20 per cent (to account for the increase in the speed) is equal to OC. With full-load current flowing through the series turns an increase in field ampere-turns from OA' to OB' occurs, such that $A'B'$ is equal to AB. This increase in ampere-turns results in a voltage at full load measured (to a different scale than used for *OC*) by *OD′*, and this voltage increased by 20 per cent, should equal *OD*; actually, if *OD′* is increased by 20 per cent it will be considerably greater than *OD*. The machine is thus considerably over-compounded for this speed, which is greater than normal.

If the machine is operated 20 per cent below normal speed, and the shunt field adjusted to give rated voltage at no load, it must operate on the magnetization curve at the point shown by *N*, such that *OC″* is equal to *OC* increased by 20 per cent. The shunt-field ampere-turns required at no load are then *OA″*. Now, at full load the series field increases the ampere-turns by an amount equal to *A″B″* (where *A″B″* is equal to *AB*) and so gives a full-load generated voltage of *OD″*. This voltage divided by 1.20 should be equal to *OD*, but evidently it will be less. Thus, at speeds lower than the rated value, the machine will be under-compounded.

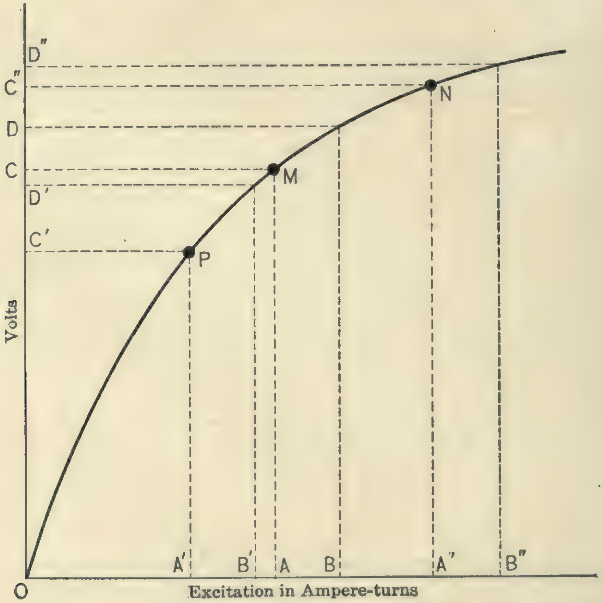


FIG. 8.

Procedure.—Connect the machine as a shunt generator as in Fig. 6 and start at rated voltage and speed with no load on the machine. Then add load, maintaining rated speed, and adjust the shunt-field resistance so that for each addition of load the voltage is brought back to its rated value. Take about eight readings up to 25 per cent overload. Read voltage, load current and shunt-field current.

Connect the machine as a compound generator as in Fig. 9 and operate it at rated speed; adjust the shunt-field resistance to give rated voltage at no load. Then with no further adjustment of the shunt field add load to the machine, maintaining rated speed. Read shunt-field current, load current and terminal voltage, getting about eight points from no load to 25 per cent overload. The curve so obtained is called the external, or compound, characteristic of the compound generator.

With the machine still connected as in Fig. 9, lower the speed to 80 per cent of its rated value; adjust the voltage, with no load on the machine, to its rated value and then take the external characteristic exactly as in the above run, keeping the speed at its subnormal value. Read same quantities as before.

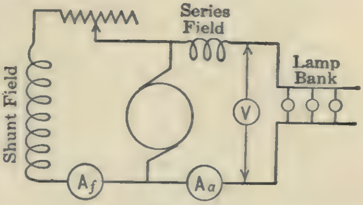


Fig. 9.

Get a similar set of readings after having adjusted the speed to a value 20 per cent higher than its rated value.

Determine the ratio of equivalent series-field turns to shunt-field turns.

Curves.—Plot the armature characteristic with shunt-field current as ordinate and load current as abscissa. On the same sheet, plot a curve expressing the relation between total magnetizing current and external current, for the compound generator operated at rated speed. If the compound generator was flat-compounded, the two curves should lie very close together.

On a second sheet, with terminal voltage as ordinates, plot the three external characteristics of the compound generator.

Questions.—

1. What is the increase in ampere-turns from no load to full load in per cent of full-load value, in the machine used as a shunt generator, flat-compounded by shunt-field adjustment?

2. Give an experimental method of obtaining the number of turns in a shunt-field winding, when it is impossible to count them.

3. Why should the resistance of a series field be made low?

4. Explain the difference in the compounding action of a generator at other than rated speed.

5. Why is the compound generator better suited for average commercial loads than the shunt generator?

6. A flat-compounded generator, with non-inductive diverter across its series field, when tested by oscillograph records, shows an instantaneous drop in terminal voltage when full load is suddenly applied, whereas when the same load is applied gradually no drop in voltage is noticed. Explain.

IV. THE SHUNT MOTOR

Object.—Study of the shunt motor. Speed characteristics. Commercial efficiency by brake test.

Theory Involved.—When the shunt motor is running at normal speed, connected across a power supply line, with the shunt field and armature circuit in parallel, on each of these circuits there is impressed the line voltage. The current through the shunt field is limited only by the ohmic resistance of the field coils and whatever external resistance may be connected in series with them. In the armature circuit there is, in addition to the resistance of the armature windings, brush contacts, etc., the counter e.m.f. generated by the armature conductors revolving in the magnetic field set up by the field current, which helps to limit the current.

After the motor has been started and brought up to speed (by the motor-starting rheostat, to be studied in the next experiment) the counter e.m.f generated by its revolving conductors is practically equal to the line e.m.f. This follows from the fact that the armature-circuit resistance is very low (necessarily so if the efficiency is to have a reasonable value) and the current taken through the armature circuit is comparatively small, when the motor is not loaded. Thus with full-load current flowing through an ordinary armature, the IR drop might be 5 per cent of the impressed, or line voltage; for a large motor it would be less than this while for a small motor it might possibly be twice this amount.

For a 110-volt motor, therefore, the full-load IR drop might be 5.5 volts at full load, and at light load it would not be more than 10 per cent of this, or 0.55 volt. The counter e.m.f. of the motor, at no load, would therefore be equal to $110 - 0.55$, or about 109.5 volts.

If the full load of this motor requires the armature current large enough to give 5.5 volts IR drop, the counter e.m.f. generated at full load must be equal to $110 - 5.5$ or 104.5 volts. The exact proportions used above hold good only if the variable brush contact drop is neglected.

In the discussion of motor speeds (Section 276, Volume I) it was shown that the counter-voltage of the motor was directly proportional to its speed, on the assumption that the field strength remained constant.

Hence, in the case considered above, the ratio of full-load speed to no-load speed is given by the ratio of 104.5 to 109.5. At no load the motor conductors generate an e.m.f. which is practically the same as that impressed; hence the no-load speed of a motor is practically the same as that at which it would have to run as a generator to give an e.m.f. equal to the line e.m.f. of the motor.

As the counter e.m.f. of the motor depends directly upon the density of field flux, for a given speed, it is apparent that if the flux density is changed by variation of field current, the counter e.m.f. *must change.* But as the c.e.m.f. must always be practically equal to the line voltage (especially at no load), it is further evident that if the field current of a shunt motor is varied, the speed must correspondingly vary. If the small IR drop at no load is neglected, the speed and flux density must vary inversely and, as the flux density is nearly proportional to the field current, it follows that the field current and speed of a shunt motor vary inversely, a 10 per cent decrease in field current being at once followed by a rise of nearly 10 per cent in speed. Speed control by field weakening was more completely discussed in Section 284, Volume I.

If a resistance is put in series with the motor armature, the speed variations from no load to full load will be much greater than before. Thus, if the full-load current of the above motor is 40 amperes and the no-load current is 5 amperes, and we insert a resistance of 1 ohm in series with the armature, the no-load c.e.m.f. must be equal to $110 - (0.55 + 5 \times 1.0) = 104.5$ volts; at full load the c.e.m.f. would be $110 - (5.5 + 40 \times 1.0) = 64.5$ volts, brush drop being again neglected.

Therefore, with the added resistance of 1 ohm in the armature circuit, the speed at no load is the same as it previously was at full load, but at full load the speed is only about half as much as it was before. Hence, the effect of resistance added in the armature circuit is to give lower speed for all loads, and a greater variation of speed as load is varied.

The direction of rotation of the ordinary motor should always be maintained the same, as the brushes become fitted, by wear, for one direction of rotation and will not fit as well for another, and sparking may result. Some motors are intended for rotation in either direction, but such are always fitted with radial brushes. The direction in which a shunt motor turns is independent of the polarity of the line to which it is connected; if the polarity is reversed by interchanging the line connections, the field current (and hence the magnetic field), and also the current through the armature, is reversed, so that the direction of the motor torque stays the same.

To reverse the direction of rotation of a shunt motor, it is necessary to reverse the connections of the line to *either* the field or armature circuit, but not both.

If a motor without commutating poles is to operate without sparking, the brushes must be set at the neutral point; this may be found experimentally, with no load on the motor, by shifting the brushes slowly forwards and backwards until the position for minimum speed is located. This will also be the point of minimum sparking.

If the brushes are moved ahead of the neutral position, the armature reaction tends to strengthen the main field, and if shifted backwards, it tends to weaken the main field. A motor with brushes ahead of the neutral point decreases its speed with increase of load, through the combined effect of increased IR drop and strengthened field. A motor with brushes behind the neutral point has its speed influenced by two opposing effects: the IR drop tends to decrease the speed, but the armature reaction, weakening the main field, tends to speed up the motor. The actual result depends upon the relative magnitude of the two effects. It is not feasible to take advantage of the effect of brush position on motor speed, because any appreciable shift from the proper neutral position will result in vicious sparking at the commutator, especially if the motor is loaded.

The efficiency of a motor is given by the ratio of power output to power input. The simplest way of measuring it is to load the motor by a brake of some kind and read the input and output for various loads. The output of the brake will generally be calculated in foot-pounds per minute, from pull on brake arm (measured with a spring balance), length of brake arm, and speed of motor in revolutions per minute. The pull on the brake arm must, of course, be the net pull; the dead-weight pull must be subtracted from all readings.

The input to the motor will be obtained as the product of line current (armature current and field current) and line voltage. This product, in watts, can be changed to foot-pounds per minute by remembering that one horsepower is equal to 746 watts, and also equal to 33,000 ft.-lbs. per min.

Instead of loading the motor with a brake, a calibrated generator is sometimes used for load. By reading the output of the generator and adding to this output the known losses of the generator, the input to the generator is obtained for any desired load. The input to the generator is evidently equal to the output of the motor, if a direct connection is used. If the generator is belted to the motor, the belt losses must be added to the generator input to get motor output; these losses are variable and difficult to determine. A possible figure is 3 per cent of the generator input for ordinary conditions, but it may be much more than this.

Procedure.—Make connections as shown in Fig. 10, selecting meters and variable resistances of suitable capacity. Most starting rheostats have four terminals, generally marked as indicated. Of the two marked " line " one will generally be a large terminal (marked *X* in the diagram); the other is a small terminal (marked *Y*). Some starting rheostats are provided with only three terminals, in which case the terminal *Y* is the one omitted and the connection $Y - A_2$, is left out.

With all of the resistance cut out of both variable rheostats, put the arm of the starting rheostat on the first contact, close the line switch and *slowly* move the arm of the starting rheostat over as far as it will go. If the connections have been properly made, the starting handle will remain in this position.

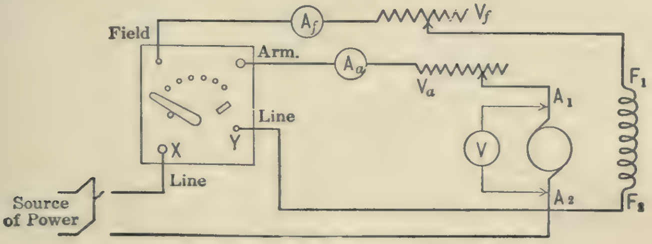


FIG. 10.

(*a*) With the motor running without load, adjust the brushes by shifting forwards and backwards, to obtain minimum speed; note that at this point the sparking is a minimum. It is, as said before, the neutral point.

(*b*) Shift the brushes forward a small amount; note speed and sparking and read the meters. Again move the brushes forward an equal amount, and repeat. Continue this until either the sparking becomes excessive or the speed rises 25 per cent. Repeat, moving the brushes backwards. If the machine assigned is provided with commutating poles, the above two tests should be performed upon another motor, not equipped with commutating poles.

(*c*) With the brushes on the neutral point and with no load on the motor, insert resistance into the shunt-field circuit by means of V_f. Take about eight readings, each time carefully reading the speed and all the meters. Do not raise the speed of the motor more than 30 per cent above the normal value. Put sufficient load upon the motor, by means of a brake, to raise the armature current to one-half rated value, and repeat, holding the armature current constant by adjustment of the brake tension. Record readings in a log as indicated in the following table:

Speed	Field Current	Armature Volts	Armature Current	Armature IR Drop	Counter E.M.F.

(d) With no load on the motor, insert resistance into the armature circuit by means of V_a, leaving V_f all cut out; read speed and all meters, taking about eight readings. Repeat, holding the armature current at one-half rated value by means of a brake.

(e) Investigate the methods of reversing the direction of rotation of the motor.

1	2	3	4	5	6	7
Volts	Armature Current	Field Current	Total Current	Speed	Spring Balance. (Initial Reading. .)	Net Pull

8	9	10	11	12	13
Watts Input	H.P. Input	Torque	H.P. Output	Per Cent Efficiency	Counter E.M.F.

(f) Remove the two variable resistances shown in Fig. 10 and operate the motor at no load, and then, by means of a brake, with 1/8, 1/4, 3/8, 1/2, 3/4, 4/4, 5/4, and 3/2 rated full-load armature current. Determine the speed carefully, and read all three meters and the brake spring balance, for each setting, recording readings as suggested in the accompanying log. Calculate motor torque, h.p output and per cent efficiency.

Curves.—Upon one sheet of cross-section paper, plot a curve between field current and speed from the results of run (*c*), and a curve between armature e.m.f. and speed from the results of run (*d*). Plot speed as ordinate in both cases.

Upon a second sheet of cross-section paper, plot a set of curves as follows: h.p. output-efficiency, h.p. output-speed, h.p. output-h.p. input, h.p. output-c.e.m.f., and torque-amperes input. Plot h.p. output and torque as abscissae.

Questions.—

1. Upon what principles does motor action depend?
2. How can the speed of a shunt motor be raised above its rated value?
3. How may it be lowered from its rated value? Explain.
4. What are the disadvantages of each method of speed variation?
5. Why is the curve between speed and field current not a straight line?
6. Why does the efficiency rise to a maximum and then decrease?
7. Why must the armature resistance of a motor be made low?
8. Why does the speed of a shunt motor fall off from no load to full load?
9. What is the speed regulation, in per cent, of the motor tested?
10. What effect does the insertion of resistance into the armature circuit of a shunt motor have on speed regulation?

V. THE MOTOR STARTING-RHEOSTAT

Object.—Study of the motor starting-rheostat and the effect of motor load on its action.

Theory Involved.—As was shown in Section 275 of Volume I, a continuous-current motor cannot be connected directly across the power supply line in starting, as an excessively large current would flow through the armature circuit, probably flashing over the commutator, burning the brush-holders and commutator, as well as blowing out the protective fuses connected in the supply line. The fuses in series with the motor may be able to carry safely 50 per cent more than the rated full-load current, or possibly twice as much as the rated current, but the current which would flow if the motor were connected directly across the line would be from five to twenty times the rated current, the higher value being for the larger motors.

All but the very smallest motors have a variable resistance put in series with the armature when starting; generally this resistance is mounted in a suitable box and the resistance is arranged for cutting out in steps as the motor speeds up. This control of the amount of resistance in the box is by means of a handle, which moves a lever over the face and makes contact with a series of buttons which are connected to the various steps of resistance.

This starting resistance is sometimes arranged to be cut out automatically as the motor accelerates; with such starters the operator merely closes a line switch and the resistance is cut out by magnetically controlled contractors at the right time. (Fig. 291, Volume I.)

The starting resistance must be able to stand the rated full-load current of the motor (or possibly 50 per cent more) for the few seconds required to accelerate the motor. In general the resistance will not stand this current continuously, or even for a few minutes, but will burn out if the large current is allowed to flow too long. Hence, in starting a motor, the starting resistance (or starting box, as it is frequently called) must not be left in the circuit longer than necessary. As soon as the motor has speeded up a certain amount, thus cutting down the current correspondingly, the starting lever must be moved over to the next point.

The heat-storage capacity of a starting rheostat should be as high as possible, and the apparatus should be fireproof. An earlier type of starting box used coiled resistance wires imbedded in sand; this was an excellent design from the electrical viewpoint but for some commercial reason did not come into general use. The best present types use resistance wires wound on porcelain tubes, covered with vitreous enamel.

As it is generally desired to give the motor the maximum turning effort during the starting period, to get quick acceleration, the shunt field is not put in series with the starting resistance (with which connection practically no torque would be developed), but full field current flows as soon as the motor is started.

The resistance in series with the armature not only limits the starting current, but, if the motor is starting under load, limits the speed at which a given torque is exerted. Thus, when the circuit is first closed, perhaps 150 per cent rated current flows and 150 per cent full-load torque is developed; the motor will speed up, thus cutting down its current according to the relation $E_{\text{line}} = IR +$ c.e.m.f., R being the total resistance of the armature circuit. As the c.e.m.f. increases with speed, the IR drop must necessarily fall off, and this can only occur by a decrease in I. As I decreases the torque decreases, and soon the developed torque is just equal to that demanded by the load. The speed will increase no more unless the developed torque is again made greater than the load torque and this is done by cutting out a section of the starting box resistance, thus decreasing R. To maintain the relation demanded by the above equation, I now increases, and so does the torque. The motor will thus again accelerate, again cutting down the current because of the increasing c.e.m.f., until the same value of torque is developed as before; the speed will now be considerably higher than it was before, however.

The sudden increase in current each time the starting resistance is reduced is occasioned by the fact that the voltage across the armature is suddenly increased, whereas the c.e.m.f. at that instant is at the value fixed by previous conditions. Finally, when all the starting resistance has been taken out, the motor is operating at full speed, directly across the line. The variation of starting current during the acceleration period is indicated in Fig. 11. The switch is closed, with the starting lever on the first " point," at the time on the curve marked 1. The current at once jumps to I, perhaps 50 per cent more than I', the rated full-load current. This point is shown at a; the motor accelerates from here and the current falls to point b, when the starting-box lever is moved over to the next point and the current again jumps to its value I, as shown at c. During the ensuing acceleration the current falls along the line *c–d,* to increase again at *d,* when the lever is moved to the third contact. When the current reaches the point *j,* the motor is developing full torque and is running at rated speed, all of the starting resistance having been cut out.

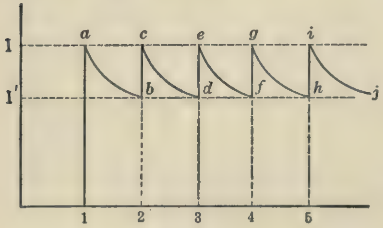


FIG. 11.

One completely equipped form of starting box is diagrammed in Fig. 12. The starting lever is shown cutting out some of the resistance. Current enters at terminal L_1, flows around solenoid *B,* through contact and switch blades *C* and *D,* to the movable arm *E.* The current then divides, part going through r_3, r_4, and r_5, to the terminal *A,* thence through the armature and so back to the other side of the line. The remainder of the current goes through r_2 and r_1, through the shunt field to the other side of the line.

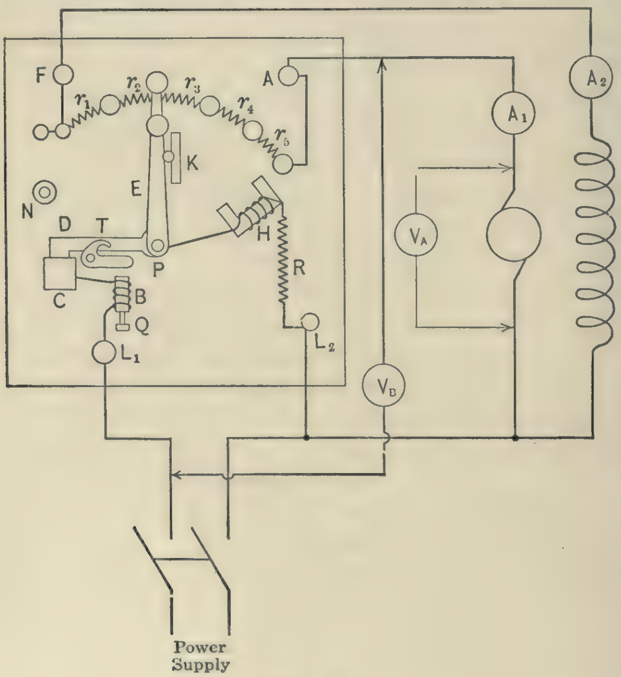


FIG. 12.

Before the motor has started, the main switch is open and arm *E* is over against the stop *N,* and is held there by a spiral spring at the pivot of the two arms. In starting the motor it is preferable to put the lever *E* on the first contact and then close the line switch. As the motor speeds up, the arm *E* is moved slowly to the right until it is on the last contact, cutting out all the resistance in the armature circuit. It is held in this position by the attraction of the electromagnet *H*, for the keeper *K*, fastened on the lever *E*. It will be noticed that in this position the resistance which was formerly in the armature circuit has now been inserted in the field circuit; this has practically no effect on the strength of the shunt field, however, because of its resistance being so very low compared to the resistance of the shunt field itself. The total amount of resistance in the box will generally be less than 5 per cent of the shunt-field resistance.

The device which holds lever *E* to the right is generally called the no-voltage release; the electromagnet is energized by current flowing from *P*, through its windings, then through the current limiting resistance *R* to the post L_2 and so to the other side of the line. If the main switch is opened, or the voltage on the supply line fails, the magnet *H* lets go of the keeper *K* and the spiral spring at *P* pulls the lever *E* back to its original position against the stop *N*, and the motor circuit is opened. This prevents the damage which would occur to the motor if the line voltage was restored with the motor, standing still, connected directly across the line, without the protecting starting resistance.

The other automatic device is the overload release, which is essentially a small circuit-breaker. Solenoid *B* is placed in series with the line circuit and if the current supplied to the motor momentarily exceeds a certain value, the plunger *Q* is pulled up and trips the trigger *T*. This releases arm *D* which is pulled over towards lever *E* by the spiral spring at *P*, thus opening the circuit by separating *C* and *D*. The lever *D* cannot be re-set without moving *E* back to the proper position for again starting the motor. If a starting box is not equipped with this overload device the line fuses are relied upon for protection in case of overload.

Procedure.—A liberally designed box is required for the experiment, one which will not overheat too quickly. A good deal of energy is transformed into heat in the box when running this test, and many boxes would be over-heated with the procedure outlined below. No soldered connections should be used on the box as these are almost sure to melt when running such a test as that given below.

Connect the motor to be used in studying the operation of the starting box as in Fig. 12. The armature ammeter used should have a range equal to twice the rated full-load current of the motor, and the two voltmeters should each have a range somewhat greater than the voltage of the line. As the readings must be taken quickly when running the test, it is advisable to put a piece of paper on each meter for quickly jotting down the readings called for. Three men should be used in this test—one to manipulate the starting lever and read one voltmeter, the second to read the remaining meters. and the third to take motor speed.

With no load on the motor, put the starting lever on the first button and close the line switch; the maximum throw of the armature ammeter (which must be well damped) is noted and recorded on its slip of paper. As soon as the speed becomes steady, as read on the tachometer, a reading of all meters is taken. Then the starting lever is moved to the second contact button; the maximum armature current is recorded and, when speed becomes steady, all meters are again read. Do similarly until all the starting resistance has been cut out. Note the time taken to accelerate up to full speed.

Now put a Prony brake on the motor and, with the motor running at full speed, tighten the brake sufficiently to make the motor draw from the line about 80 per cent of its rated full-load current. Without changing the tightness of the brake, stop the motor and proceed as before for no load. Note the time taken for the motor to accelerate to full speed.

In this run it is imperative that no time be lost; as soon as the speed becomes steady, move the lever at once to the next contact, otherwise the box will surely overheat and perhaps burn out.

1	2	3	4	5	6	7	8	9
Arm. Volts V_A	Box Volts V_B	Line Volts	Arm. Current		Field Current	C.E.M.F.	Speed	Resistance in Box
			Max.	Steady				

After the second test determine the armature-circuit resistance for several values of current, covering the range of current used in the test. Put readings in a suitable log form (about as given in the accompanying form); in calculating the c.e.m.f. and resistance of the box, use only the steady values of current, i.e., those read after the speed has become constant.

Obtain approximately the volume of the space inside the box.

Curves.—Plot curves for armature current during starting, about as given in Fig. 11, curves to be plotted for both runs. Also for both tests plot curves between speed and counter e.m.f.

Questions.—

1. A sand-filled box safely starts a certain motor under load, taking ten seconds for the starting period, reaching maximum safe temperature of the resistances used. How will the box behave if the sand is taken out?

2. Calculate how much energy was changed into heat in the starting box you used for both runs.

3. What will probably happen to a starting box if the motor is started too slowly? Too rapidly?

4. Explain the change in shunt-field current during the starting period.

5. From the data you have, how could the shunt-field resistance be calculated, the accuracy of the field ammeter being questionable?

6. If the box were filled with water (possible short circuits being neglected), how long might the starting period be without boiling the water, the motor accelerating under 80 per cent load as in the last run?

7. What determines the steady speed and armature current for each contact point of the starting box?

8. What difference should there be in the design of a box from the ordinary design, if the motor to be started is for running a punch press, and so has a very heavy flywheel on its shaft?

VI. EFFICIENCY BY STRAY POWER METHOD

Object.—To obtain the conventional efficiency of a shunt motor by the stray power method.

Theory Involved.—The easiest way to measure the efficiency of a motor is to measure its output and input and calculate their ratio as was done in the previous test. The scheme of loading a motor by friction brake is practically never used, however, for motors above perhaps 10 h.p. rating, as there are at least three disadvantages in this method which may be eliminated by using the method to be described below. These disadvantages are: (*a*) Large amount of energy used and wasted, (*b*) Difficulty in getting the requisite loading apparatus in the form of brakes which will absorb large amounts of energy, (*c*) The efficiency cannot be obtained very accurately, probably not better than about 1 to 2 per cent in the average test.

For large amounts of power, water-cooled brakes are used, but their operation requires quite some attention and it is not possible to read the output very accurately with brakes. If brake tests are to be used the test shop must be wired and equipped with a power supply considerably in excess of that required by the largest machine ever to be put through the shop, and this expensive installation is not necessary if the stray power method of determining efficiency is used.

In a large test shop equipped with many auxiliary machines, a loading test may well be used, in which the motor load is absorbed by a generator (preferably directly connected to the motor) and the output of the generator is put back into the power supply line. This scheme is called the " pump-back " test, as most of the power taken by the motor from the supply is pumped back into the same line by the generator used for load. Many generators of various capacities and speeds must be available in the shop if this scheme is to be much used, and their losses must be accurately known. Such a generator load, the losses of the generator being accurately known, is frequently referred to as an electric dynamometer. Such a loading device is very generally used in testing gas engines, etc.

The accuracy of the output-input method of getting efficiency must quite evidently be limited by the accuracy with which the meters can be read and calibrated. The reading of the average meter may not be reliable to better than 1 per cent, especially at the lower part of the scale, and if the input is obtained by the product of volts and amperes, with a possible error in each of them, an error of 2 per cent is possible in the calculated input. If there is an error of 1 per cent in the speed, and an error of 1 per cent in reading brake torque, an error of 2 per cent in the output is possible. If (as is, of course, very unlikely) all these errors occur simultaneously high (low) in the input and low (high) in the output, respectively, an error of 4 per cent in the calculated efficiency is possible. Such an error is, of course, not probable, as it is most likely that some errors will be compensated by others, but even so it will be realized that this method of determining efficiency is not very accurate.

The stray power method does not require that the motor be loaded at all; the various losses which would occur if the motor were loaded are measured as accurately as possible, generally plotted in the form of curves, and their sum plotted as the " total loss " curve; this curve is generally plotted against motor input. At any assumed input the output may be at once determined by subtracting from the assumed input the total losses which would occur in the motor; the efficiency is then at once obtained.

This idea is expressed by the equation:

$$\text{Efficiency} = \frac{\text{Input} - \text{losses}}{\text{Input}}.$$

The efficiency so determined is generally called the conventional efficiency, as contrasted with the directly measured efficiency. It is also frequently called the predicted efficiency.

It is evident that, to apply this method, all of the losses must be measured, and if they vary with load they must be measured for several values of assumed input. As input is equal to line voltage multiplied by line current, and as the line voltage is a constant, the losses are generally plotted in terms of the amperes input to the motor. As will be shown later, these losses are measured with no load on the motor and it is assumed that they are the same when the motor is loaded. We know that such is not the fact, and hence we know that some error is made in this method of getting the efficiency; even so, allowing an unreasonably large error in measuring the losses, the conventional efficiency is much more accurate than the directly measured efficiency.

This will be appreciated by inspection of the equation used, as given above. At full load the total losses might be 15 per cent of the input, and even if an error of 10 per cent had been made in the determination of these losses the resulting error in the calculated efficiency would be only 1.5 per cent, probably even then less than the error in the other method.

The losses in any generator or motor can be divided as follows:

- Losses
  - Copper
    - Copper loss in the armature circuit.
    - Copper loss in the field circuit.
  - Stray power
    - Friction, or mechanical, losses
      - Bearing friction.
      - Air friction, or windage.
      - Brush friction.
    - Iron, or core, losses
      - Hysteresis loss.
      - Eddy current loss.

Upon consideration of the copper losses, it is evident that if we know the resistance of the armature circuit we can immediately compute the I^2R loss for any value of current. This is true for a current actually measured or assumed, and the same evidently applies to the field circuit.

The friction losses will vary directly with the speed within the limits between which the machine is ordinarily operated. The hysteresis loss, however, varies directly with the speed and as the 1.6 power of the maximum flux density in the armature iron. The eddy-current loss varies as the square of both the speed and flux density.

In the shunt motor, as commercially operated, two factors are considered constant, namely, the line voltage and the shunt-field current. For the moment we neglect the effect of armature reaction on the flux density in the armature iron.

With increase in load on the motor there is a slight drop in speed, accompanied by a decrease in the c.e.m.f. From the equation $e = K\phi N$ (N being speed, K a constant, and ϕ the flux) it follows that if the flux is considered constant, the c.e.m.f. must be directly proportional to the speed. The armature current, however, must be fixed by the relation $E_{\text{line}} = IR +$ c.e.m.f., so that if we know the resistance of the armature we can calculate the c.e.m.f. for any assumed value of armature current. So, if we know the value of speed and c.e.m.f. for some value of armature current, we can calculate the c.e.m.f., and hence the speed, for any other assumed armature current. It is thus possible to predict the speed-load curve of a shunt motor provided that we know the armature resistance, and the speed at some one value of armature current.

Let us consider then that we know the values of armature and field currents and speed, when the motor is running free, with rated voltage on both armature and field. From the name-plate of the motor we can find what the manufacturer intends the full-load current of the motor to be. From this full-load current we can calculate the value of full-load c.e.m.f. and so, by direct proportion, obtain the full-load speed. This will, of course, be somewhat lower than the no-load speed, generally about 5 per cent lower.

Knowing the full-load armature current, we also know the full-load input, and as we know the value of the armature and field resistances we can readily calculate the armature- and field-circuit copper losses. We have now to see how we can get the stray power losses.

When a motor is running free the entire input is used in overcoming its own losses. If the known copper losses are subtracted from the no-load input the difference must be the stray power losses, good, of course, only for that particular speed and field current.

We have presumably calculated the full-load speed of the motor; if then we run the motor light (free) at this speed, and with normal field current, the input, minus the known losses, must give us the stray power for full load, aside from the effect of armature reaction. The stray power for other speeds may be obtained in a similar manner.

The effect of armature reaction, proportional to the load current and varying with the brush position, is to modify somewhat the iron loss component of the stray power loss. If we neglect this effect, however, it is possible to obtain the full-load stray power, or stray power at any fractional load, without actually loading the motor, as stated above. The actual effect of the armature reaction on the iron losses is difficult to predict. There may be a slight weakening of the main field, and thus a slight increase of speed above the predicted value, but, more important, there will be a considerable distortion in the main field, resulting in a much greater density in the armature iron with load than without load. This effect is well shown by the field distributions given in the form of oscillograms throughout the text of Volume I. The hysteresis and eddy-current losses undoubtedly increase therefore with load, and quite appreciably; however, as these losses are only a small part of the total losses, and as a considerable error may be made in the loss measurements without seriously affecting the efficiency calculated, this method proves to be the most suitable we have for getting efficiencies of electrical machines.

Procedure.—Before starting the test, run the motor at full load for about fifteen minutes to warm it up and then determine the resistance drop of the armature circuit for eight values of current between a very low value (2 to 3 per cent of rated value) and 150 per cent rated value, and plot the values in the form of a curve. Also measure the resistance of the shunt-field circuit.

Connect the motor as shown in Fig. 13, the source of power being preferably a laboratory generator, the terminal voltage of which is under control. With both VR_a and VR_f cut out, operate the motor with rated voltage across both armature and field. Measure the speed and both armature and field currents very carefully. These should be read to at least 1 per cent accuracy. If necessary use two meters in the armature circuit, one of high range connected as shown in Fig. 13, and another in series with it, having a range not more than 10 per cent rated current of the motor. This low range meter should have a short-circuiting switch around it, closed when starting the motor; this short-circuiting switch should not be opened until the motor has reached full speed.

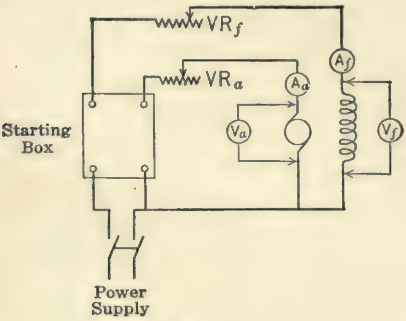


Fig. 13.

Knowing the full-load armature current from the motor's name-plate, and knowing the armature resistance drop from the first part of the test, calculate the c.e.m.f. for 12.5, 25, 37.5, 50, 75, 100, 125, and 150 per cent full-load armature current. Then calculate the c.e.m.f. with the data obtained from the running-light condition, and from the speed there measured, calculate the speeds corresponding to the armature currents assumed above.

Then operate the machine at normal field current and at the calculated speeds and read all meters. A good method of procedure is to set the value of supply line voltage a few volts above the rated value for the machine and then to insert resistance into the field circuit by means of VR_f until normal-field current is flowing. Then decrease the speed of the machine to the desired value by inserting resistance into the armature circuit by VR_a.

In the log, as shown in the suggested table, part *a* is for the operation at no load to determine the stray power corresponding to each load speed. All the columns in part *b* are to be calculated or assumed, except column 9, which is taken from part *a*.

Curves.—Plot the loss curves determined for the machine, about as shown in Fig. 307 of Volume I; also plot the curves of calculated efficiency and speed, using same scale for abscissa as for the loss curves. If this experiment was performed on the same machine as was used in the brake test for efficiency, plot the points of efficiency obtained from that test on this curve sheet, for comparison.

PART *a*.—MACHINE RUNNING LIGHT

A	B	C	D	E	F	G	H	I	J	K
R.P.M. Calculated	Arm. Current Running Light	Field Current (Constant)	Arm. Volts	Field Volts	Arm. Input in Watts	Field Input in Watts	Total Input in Watts	Arm. I^2R Loss	Total I^2R Loss	Stray Power Loss
					$B \times D$	$C \times E$	$F+G$		$I+G$	$H-J$

PART *b*.—PREDICTED OPERATION WHEN LOADED

1	2	3	4	5	6	7	8	9	10	11	12	13
R.P.M. Calculated	Line Volts (rated)	Arm. Current Values Assumed	Field Current	Total Current	Watts Input	Arm. I^2R Loss	Field I^2R Loss	Stray Power Loss	Total Losses	Watts Output	H.P. Output	Efficiency in Per ct.
				3+4	2×5		2×4	*K* from Part *a*	7+8+9	6−10	11÷746	(11÷6 ×100)

Questions.—

1. What are the assumptions upon which the stray power method of determining the efficiency of a shunt motor is based?

2. What are the advantages of the method, compared to brake method?

3. How do the losses vary from no load to full load?

4. Why does the efficiency at first rise and then fall as the load increases?

5. Find out, by calculus, what relation exists between the fixed losses and variable losses, at the point of maximum efficiency. Assume stray power constant.

6. How much would the full-load efficiency, as determined in this test, be changed, if the no-load stray power value, operating at rated voltage across the armature and field, were used, instead of that obtained by operating at the calculated full-load speed?

7. Suppose that, due to armature reaction, the field is so distorted that the maximum field flux density under actual load condition is 50 per cent greater than that existing when the stray-power loss was obtained. Assuming the core losses are 60 per cent of the stray power and that the hysteresis loss is 80 per cent of the core loss (with the lower flux density) how much error is made in the efficiency prediction?

VII. THE SERIES MOTOR

Object.—Study of the operation of a series motor. Relation of speed and efficiency to output. Effect of line voltage on speed.

Theory Involved.—As the impressed e.m.f. on any motor must be equal to the sum of the IR drops and the c.e.m.f generated, and as the series motor has its field connected directly in series with its armature, it is evident that we must have $E_{\text{line}} = I(R_{\text{arm}} + R_{\text{field}}) + \text{c.e.m.f.}$

Now, in any motor, c.e.m.f. $= K\phi N$, where ϕ is the motor flux, N is the speed, and K is a constant; in the series motor, as the flux is produced by the same current as that which flows through the armature, we must have $\phi = kI$, so that c.e.m.f. $= K'IN$, and we can then rewrite the first equation:

$$E_{\text{line}} = I(R_{\text{arm}} + R_{\text{field}} + K'N),$$

so that

$$N = \frac{E_{\text{line}} - I(R_{\text{arm}} + R_{\text{field}})}{K'I}, \quad . \quad . \quad . \quad . \quad . \quad (1)$$

If the resistance drop in the field and armature is neglected, this expression shows that the speed of a series motor follows an equilateral hyperbola, when plotted against the current; twice the speed requires that one-half the current flows.

There are two factors which tend to change somewhat the shape of this curve from the hyperbolic form; at the high speeds the friction losses increase very rapidly, and at the low speeds, where the current has very high values, the iron of the magnetic circuit tends to become saturated, so that the flux is no longer proportional to the current; hence the speed drop is not quite as rapid as the elementary analysis given above would predict. In Fig. 14 an equilateral hyperbola is shown in the dotted line, and in the full-line curve is given the form of the speed-load curve of a series motor.

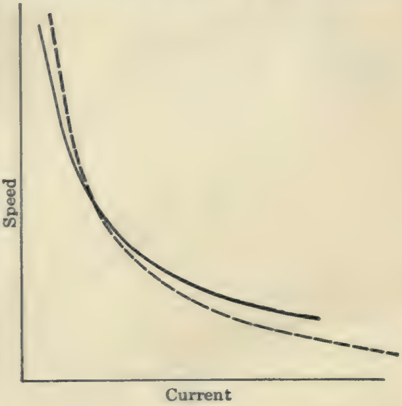


FIG. 14.

Because of the behavior of the series motor at very light loads it must never be completely freed from load or it will " run away " and probably destroy its windings as a result of the high centrifugal forces set up at the high speeds it would reach. In laboratories it is well to have a centrifugal switch on the motor shaft which serves to close a relay, this opening the line if the motor speed exceeds a certain predetermined value.

From Eq. (1) it can be seen that if the impressed voltage is decreased the speed will correspondingly drop; the decrease in speed is not quite proportional to the decrease in line voltage because of the effect of the resistance drops in the armature and series field. These are always kept small, however, for reasons of efficiency.

Procedure.—Determine the resistance of the armature and series field in series, by putting a suitable lamp bank or other variable resistance in series, and clamping the armature so that it cannot rotate; read the drop across each separately and so get these resistances for about six values of current, up to 150 per cent of rated current.

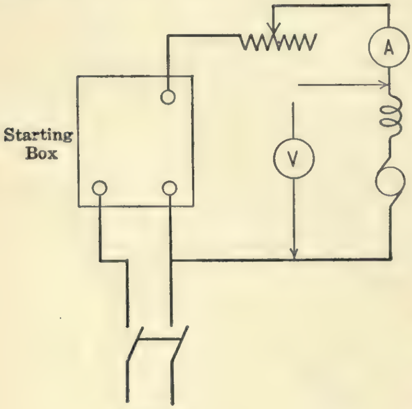


FIG. 15.

Make connections as shown in Fig. 15, choosing the ammeter used, and the variable resistance, with a capacity about twice as much as the rated full-load current of the motor. Start the motor, and, by means of the variable resistance reduce the voltage across the motor to one-half its rated value. Starting with a very small load (no load at all if the resulting speed is not too high) take a reading of current and speed; gradually increase the motor load by tightening the brake, always maintaining the voltage impressed on the motor at one-half rated value. Take about eight readings of current, the spring balance, and corresponding speed, up to 50 per cent overload for the motor. If a constant potential line, of one-half the rated voltage of the motor, is available, the variable resistance need not be used, and the performance of the test will be much facilitated.

Tabulate the data obtained in four columns; voltage across the motor, c.e.m.f., current, and speed.

Next impress full voltage on the motor and adjust the brake until the motor takes about 60 per cent of its rated current. Read speed and voltage. Then decrease the voltage impressed on the motor by about 10 per cent and adjust the current (by means of the brake) to the same value as before and again take a set of readings. Repeat this operation, continually decreasing the voltage on the motor in even steps, until about eight readings have been obtained.

Next, with rated voltage on the motor, make a complete brake test up to 50 per cent overload current. If the motor is fitted with a speed-limiting-device allow the motor to run free and determine the current and speed just as the device cuts the motor from the supply line. If no safety device is fitted to the motor, take, as the maximum safe speed, 300 per cent of the rated full-load speed; it is well to take this value as the upper speed limit unless advised by the instructor that higher is permissible. Record readings in a table similar to that used for the efficiency run on a shunt motor.

Curves.—Plot a curve between current and motor resistances. Upon the same sheet plot a curve between speed and impressed voltage, using speed for ordinates, from the results of the second run. Upon a second sheet plot speed-current curves, torque-current curves, and efficiency-current curves, from the first and third run. Plot current as abscissa for the last six curves.

Questions.—

1. Explain why the speed of a series motor varies so much with load.

2. A series and a shunt motor have the same horsepower rating at full load. Which is probably the larger, and why?

3. Why is the series motor better adapted to the frequent starting of heavy loads than the shunt motor?

4. Why is the torque-current curve concave at its lower end, and then more like a straight line at its upper end?

5. What is the effect of lowering the voltage impressed on a series motor, as regards speed and torque, the load being so adjusted as to keep the current constant?

6. Why should a series motor never be belt-connected to its load?

7. A 110-volt series motor has maximum efficiency of 90 per cent at full load; about how much voltage would be required to force full-load current through it at standstill?

VIII. CURRENT-TORQUE CURVES OF MOTORS

Object.—To study the current-torque curves (starting-torque curves) of various types of motors.

Theory Involved.—The torque exerted by a motor when starting is one of its most important characteristics; the torque per ampere gives a direct measure of the relative ease with which different motors would accelerate under load, when drawing the same current from the line. Motors having the highest torque per ampere are evidently the most desirable, other things being equal, as they will accelerate in the shortest time and give the least disturbance to the line voltage when starting.

A motor requiring an excessive line current to pick up its load (one having the least torque per ampere) is also difficult to fuse; if the fuses put in the supply line have such a current capacity that they do not blow during the starting period, they will evidently not protect the motor properly against overloads when operating. Thus, if a certain motor, which draws 100 amperes during the ten seconds or so required for starting, is rated at 50 amperes full load, 100 ampere fuses at least will be required to take care of the current flow while starting; if during operation a continuous overload current of 90 amperes is demanded of the motor, because of the excessive mechanical work it is called upon to do, the fuses will not blow. But a load of 90 amperes would probably spoil the insulation of the armature coils in an hour or less.

From this it is seen that a motor which has frequently to pick up a load, which demands the development of a good deal of torque, must be so built that it develops a high torque per ampere.

In a shunt-wound motor the field strength is the same whatever the armature current may be, if the effect of armature reaction is temporarily neglected. In the series motor the field strength is nearly proportional to the armature current; in fact, it is exactly so until the current becomes so large that the iron of the magnetic circuit approaches saturation. In the compound motor the field strength increases somewhat with the increase of armature current, but not as much as in the case of the series motor.

We should expect then, that in the case of the shunt motor the torque would increase directly with the armature current, in the series motor with the square of the armature current, and in the compound motor with some power of the armature current between the first and second.

The question might well be asked, "If the extra field strength of the series motor during the starting period, when perhaps 150 per cent rated current flows, is an advantage, giving a higher torque per ampere than does a shunt motor, why is not the shunt motor designed to operate with a flux density equal to that developed by the series motor while starting?" The answer is, that if such a high field strength were used in a motor running at rated speed, the core would soon become so hot that it would burn the insulation off the windings. In the series motor this effect is cared for automatically; the speed is always low when the armature and field current is large (see Fig. 14), and as the core loss depends upon the speed as well as the field density, the loss is not excessive even when the current and field density are much above the normal running values. As the speed increases, tending to give excessive core loss, the flux density automatically falls, because the current always decreases as the speed increases.

In the shunt motor, on the other hand, the flux density is independent of the speed, so that as the motor speeded up, the high density used in starting would be sure to overheat the motor. It might be suggested that only part of the field turns be used while starting, thus increasing the field current, but this would accomplish nothing but overheating of the field windings; the resistance of the field windings might be such that ordinarily a resistance would have to be inserted in series to keep the field current to a safe value, and that this resistance might be cut out while starting, but this would be uneconomical of material and power. The ordinary shunt motor does not generally require a field rheostat.

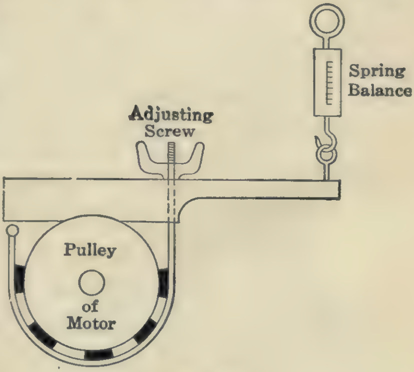


Fig. 16.

In order to determine the torque generated by a motor when standing still, some form of Prony brake is clamped fast upon its pulley, as is shown in Fig. 16. When current flows through the armature and fields, let us suppose that the torque developed is such as to tend to rotate the armature in a clockwise direction. If the brake arm is moved slowly upwards against the torque of the motor, the pull required may be resolved into three components: first, that required to lift the brake arm against gravity; second, that required to overcome the friction of the bearings and brushes; third, that required to overcome the torque due to the armature current. This might be written

$$A_1 \times l = T + w + f,$$

in which A_1 = the reading of the spring balance when lifting the brake arm;
l = the length of the brake arm;
w = the torque due to the weight of the brake arm;
f = the torque due to motor friction, and
T = the torque to be determined.

If another reading of the spring balance is taken when the brake arm is allowed to fall slowly, the force due to friction acts in the opposite direction to the one it had before; so that if the new reading of the balance is A_2, we have

$$A_2 \times l = T + w - f.$$

Adding these two equations we get

$$T + w = \left(\frac{A_1 + A_2}{2}\right) \times l,$$

which expression eliminates the friction.

To determine w, the torque due to the weight of the brake arm, readings of the spring balance are taken with the brake moving slowly up and slowly down, with the field current and armature current reduced to zero. The average of these two readings of the balance gives the torque due to the brake-arm weight. This being known, the torque due to the current through the motor can be obtained from the above expression.

Procedure.—Two motors are required for this test, a compound motor and a series motor; the shunt motor characteristics can be obtained from the compound motor by leaving its series field open. The compound motor to be used should be connected as in Fig. 17, the shunt field being excited by the potentiometer connection and the series field left unused. The motor is thus really a shunt motor, although with somewhat less field excitation than a normal shunt motor would generally have.

By means of the variable resistance, set the value of the field current a trifle lower than one-half of its rated value (obtained by dividing the rated voltage of the motor by the field resistance, or by reading the field current when normal voltage is impressed on the field circuit) and then vary the armature current from zero up to 150 per cent of its rated value in about eight steps, taking torque and current readings as previously described. Keep the shunt-field current constant during this test.

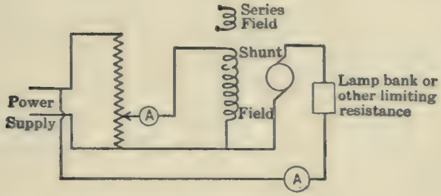


Fig. 17.

Raise the field current to double the value used in the previous run and proceed as just described, getting eight more readings.

For the third run, set the armature current at its rated full-load value and vary the shunt-field current from zero to normal value, taking readings as before.

Now connect the series field in series with the armature, so as to make a cumulative compound motor. Keeping the shunt-field current first at half value, and then at nearly full value, vary the armature current and get readings as for the first and second tests outlined above.

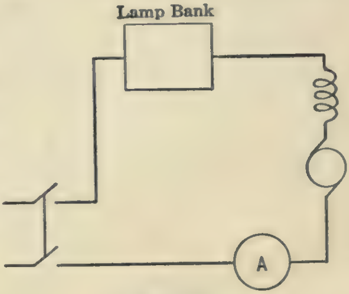


Fig. 18.

The series motor tested should have the same horsepower rating and voltage, as the other motor just tested, in order that proper comparisons may be made. Make the connections as indicated in Fig. 18 and get the starting torque for about eight values of current from zero to 150 per cent rated current.

Curves.—Plot curves of torque and current through the armature for all runs where the field current was constant, using current as abscissa; also plot the torque per ampere against armature current. Corresponding curves for the three motors are to be plotted on the same sheet. Plot one curve for the shunt motor, of torque against field current, using field current as abscissa.

Questions.—

1. Why are the current-torque curves for the shunt motor straight lines?

2. Why is the curve concave upward, at first, for the series motor?

3. Just why does the torque per ampere for the shunt motor decrease with increasing current, and not for the compound and series motors?

4. What would the current-torque curve for the compound motor have looked like if the series field had been reversed?

5. Under what condition would the torque per ampere of the series motor become constant with increasing current?

6. What effect would it have on the starting torque of a shunt motor if only half the turns were used, this half field being connected across the line as was the full number of turns?

7. If a shunt motor were equipped with a compensating winding in the pole faces, what would be its effect on the form of the current-torque curve of the motor? On the torque-per-ampere curve?

8. If the brushes of a shunt motor were shifted considerably ahead of the neutral position, how would the form of the current-torque curve be changed compared to the curve with brushes normally set?

9. In this test what would be the effect if the armature conductors were made of German-silver instead of copper, same size as the copper?

IX. SHUNT-WOUND GENERATORS IN PARALLEL

Object.—To study the action of shunt-wound generators operating in parallel.

Theory Involved.—The necessity of having at least two, and generally several, machines operating in parallel in a given power station was analyzed in Section 234, Volume I; it was there pointed out that both for reliability of power service and for efficient operation several machines are always installed.

These machines might be connected together in either series or parallel arrangement and in so far as their electrical characteristics were concerned the operation would be satisfactory, but the series connection is entirely unsuited for the ordinary load supplied by a power station. With the one exception of street-lighting circuits, the various pieces of apparatus used by the ordinary power consumer are designed for parallel operation, on a constant-voltage system.

If, for example, one attempted to operate, say, an electric toaster in series with an incandescent lamp, the lamp, requiring about 1 ampere, would evidently not permit the passage of sufficient current to get the toaster red hot, this generally requiring about 7 amperes.

Furthermore, even if all pieces of apparatus should be designed for the same current so that the series connection might be permissible from that viewpoint, the voltage supplied would necessarily have to go up and down with the number of utensils a householder might be using. Consideration of the problem shows that such a series arrangement of the diverse pieces of apparatus supplied from the power lines, for many different customers, could not possibly work. Constant voltage power must be supplied to the customer, no matter how many devices he may desire to have connected to the line.

Now, if such is the case, it is evident that the connections of the different generators in a power house must be a parallel arrangement; as the load demanded from the station increases, with increasing number of lamps, utensils, and other pieces of apparatus, one generator can no longer supply the demand, and another must be put into operation. If this second machine should be connected in series with the one already operating, the voltage supplied by the station would be at once doubled, and all the apparatus connected to the line would be burned out; even if this did not happen, the current capacity of the station would be no greater than it was before. If, however, the second generator is connected in parallel with the first, the voltage supplied by the station remains practically the same as it was when only one machine was operating, but the possible current output of the station has been doubled; this change is just what the increasing load demands.

Although shunt generators are seldom used for station work, compound-wound generators serving the purpose so much better, it is advisable to investigate the action of shunt-wound generators operating in parallel in order that the more difficult case of compound generators may be understood. (The action of compound-wound generators operating in parallel will be considered in the next experiment.)

The analysis of the question may be most easily made by supposing first that one machine (say, No. 1) is already connected to the bus-bars and carrying load, and that whatever manipulation is carried out with the second generator (No. 2), the bus-bar voltage will be assumed constant. This latter will not generally be the case, but it makes the first analysis simpler.

Consider the generators connected as in Fig. 19. Generator No. 1 is supplying whatever load is connected to the bus-bars, and it is desired to connect machine No. 2 to the bus-bars and to divide the load between them.

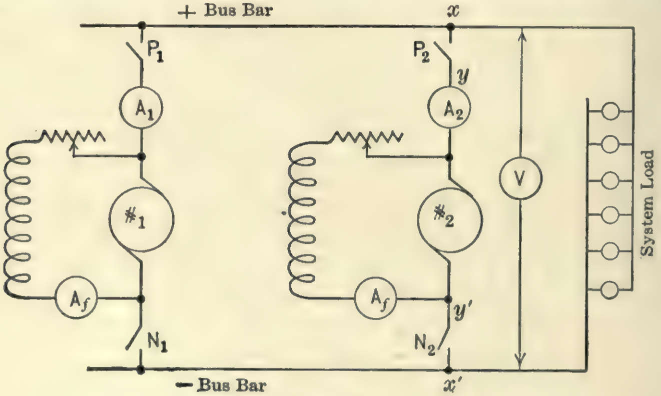


FIG. 19.

Let E_b = voltage between the bus-bars;
E''_g = generated voltage of generator No. 2;
R_a = armature resistance of generator No. 2;
I_2 = armature current of generator No. 2.

If the generated voltage of generator No. 2, E''_g, is exactly equal and opposite to the voltage between the bus-bars, E_b, it is evident that when switches P_2 and N_2 are closed, no current will flow through the armature circuit of generator No. 2.

If E''_g is not equal to E_b then current will flow upon closing of the switches, according to the equation:

$$I_2 = \frac{E_b - E''_g}{R_a}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

The *magnitude* of the current will be determined by the difference in E_b and E''_g, and the *direction* of the current will depend upon whether E''_g is greater or less than E_b. If E''_g is greater than E_b, current will flow in the same direction as E''_g tends to make it flow; i.e., the machine will act as a generator. If E''_g is less than E_b, then the voltage of the bus-bars forces current to flow through the armature circuit of generator No. 2, against its generated e.m.f. Machine No. 2 therefore acts as a motor, drawing power from the bus-bars instead of furnishing power to them.

If the switches N_2 and P_2 are closed when E''_g is not nearly equal and opposite to E_b, an excessive current must flow so that Eq. (2) may be satisfied. This sudden rush of current will disturb the line voltage, may blow fuses and circuit breakers, and even injure the machines.

It has been said that E''_g must be opposite to E_b; this is sometimes expressed by saying that the generators must be connected with *proper polarity.* The necessity of this precaution is almost self-evident. Suppose that E''_g and E_b were not opposite, i.e., that they were of incorrect polarity. As soon as the switches P_2 and N_2 were closed, both E''_g and E_b would tend to force current in the same direction through the circuit composed of the two armatures and the bus-bars, all in series. As the resistance of this local circuit is very low, the conditions would be the same as if each machine were short-circuited upon itself.

To test for polarity, switch N_2 may be closed and a voltmeter of range at least twice the voltage of the machines connected across P_2. If generator No. 2 is connected with correct polarity, the voltmeter reading will be $E_b - E''_g$; if connected with incorrect polarity, the voltmeter reading will be $E_b + E''_g$. Another way of testing for polarity is to connect a voltmeter (one of range equal to the bus-bar voltage is sufficient) across the bus-bars (points xx') and then transfer the voltmeter leads, *without* interchanging them, to the points yy'. This transferring of the voltmeter is usually done on station switchboards by a voltmeter switch as shown in Fig. 270, Volume I. If the voltmeter deflects the same way in both cases the polarity is correct; if not, the connections of generator No. 2 to the bus-bar switches must be reversed, or else the generator must be made to build up with opposite polarity.

If generator No. 2 has been brought up to its rated speed, its voltage adjusted to be equal to the bus-bar voltage, and the polarity test satisfied, switches P_2 and N_2 may be closed and no current will flow through its armature circuit. With the bus-bar voltage assumed as constant, and the load current considered constant, it is evident from Eq. (2) that the current I_2 will depend directly upon the value of E''_g. If the generated voltage of machine No. 2, E''_g, is increased, by decreasing the resistance of its shunt-field circuit, it will deliver current to the bus-bars, the amount of current depending upon how much E''_g is increased; if E''_g is decreased, by inserting resistance into the shunt-field circuit, the machine will take current from the bus-bars. The division of load between two shunt-wound generators operating in parallel is thus always at the command of the operator; by proper adjustment of the field resistances, the load may be shifted from one generator to the other, at will.

With the load once equally divided between two generators operating in parallel, the question arises whether the division will remain equal as the load varies. This has been analyzed in Section 236, Volume I.

Procedure.—Connect the shunt generators to be operated in parallel, as in Fig. 19. Connect one of the generators to the bus-bars and put approximately rated full load upon it by means of lamps or other convenient means. Then bring the second generator up to rated speed, build up its voltage to that of the bus-bars, and having determined that it will come in with proper polarity, close its line switches. Strengthen the field of the generator just brought in until it is supplying half of the load current, and then weaken the field of the first machine until it is supplying no current to the load. Further weaken the field of the first generator until it is operating as a motor; this fact will be indicated by the fact that the ammeter in its armature circuit has reversed. Note that the shunt-field current continues to flow in the same direction, whether the machine is operating as a generator or as a motor. Then bring the armature current of the first generator to zero and disconnect it from the bus-bars. Continue this procedure until sufficient practice has been had, in placing the machines on and off the bus-bars and in shifting the load back and forth.

(*a*) With no load on the system, place both generators in parallel upon the bus-bars and adjust the voltage across the bus-bars to rated value with no armature current in either machine. Then add load in equal steps up to the full-load value of each machine, keeping it divided equally between the two generators by adjustment of their respective field rheostats. The system voltage is to be kept constant at rated value and machine speeds at rated values. Read all meters, using a log of the form suggested in the following table:

	Generator No. 1				Generator No. 2				System	
1	2	3	4	5	6	7	8	9	10	11
Bus-bar Voltage	External Current	Field Current	Kw. Output	Speed	External Current	Field Current	Kw. Output	Speed	Load Current	Kw. Output

(*b*) Starting as in the previous run, with no load on the system and bus-bar voltage at rated value, add load to the system, but allow the load current to divide between the machines as it will. Allow the voltage to vary, but keep speeds constant at their rated values.

After run *b*, with about half rated load on each generator, investigate the effect of shifting the brushes of one generator forward and backward. Note the readings of all the meters. Be careful not to shift the brushes too far, especially if the machines are equipped with commutating poles.

Curves.—Upon one sheet of cross-section paper, plot three curves (one for run *a* and two for run *b*), between bus-bar voltage (ordinates) and individual external currents. Upon a second sheet of paper plot two curves, for run *a*, between individual shunt-field currents (ordinates) and load current.

Questions.—

1. What precautions must be taken in connecting shunt generators for parallel operation?

2. Why, if left without adjustment, will the generators not divide the load on the system in proportion to their rated outputs?

3. Is the parallel operation of shunt generators important from a commercial standpoint?

4. Explain the forms of the curves obtained.

5. Explain the effects brought about by shifting the brushes of one of the shunt-wound generators operated in parallel.

6. If a shunt generator is connected to the bus-bars, on which several others are already operating in parallel, and the polarity of the incoming machine is reversed, about how much current (in terms of full-load current) will flow through it, instantaneously?

7. How could this answer be approximately verified, from your knowledge of the efficiency of a shunt generator?

X. COMPOUND-WOUND GENERATORS IN PARALLEL

Object.—To study the action of compound-wound generators operating in parallel. Action of the equalizer bus, and its effect on load division.

Theory Involved.—Shunt-wound generators always show a terminal voltage decreasing with increase of load; because of this fact they are perfectly stable in their operation when connected in parallel on the same load. Compound-wound generators practically always are so designed that their terminal voltages rise with load increase, possibly 10 per cent from no load to full load. This characteristic of compound generators makes them inherently unstable when connected in parallel, unless a special equalizer bus is also used.

When connecting compound generators in parallel, evidently the same precautions regarding polarity must be observed as was the case for shunt-wound generators; if the incoming machine has built up with incorrect polarity its residual magnetism must be reversed so that it will build up with the proper polarity. In a station it would evidently be impossible to reverse the connections of the generators to the bus-bars, even if it were desired to do so, to overcome the difficulty of reversed polarity of the incoming machine. But in the laboratory, where flexible cables are often used to make connections, it might be the first idea to reverse the armature terminals of the incoming machine. The connection scheme for operating two compound generators in parallel is shown in Fig. 20, and a study of this diagram will show that if machine No. 2, the incoming one, should be connected to the bus-bars in reversed sense, a short circuit would result as soon as the switches in the equalizer bus were closed. If the terminals of the armature (and shunt field in parallel with it) were reversed, leaving the series field and equalizer connections as they are shown in the diagram, the difficulty as regards polarity would be overcome and no short circuit would result, but machine No. 2 would have been changed, by this reversal of connections, to a differential generator and thus, with its falling external characteristic, could evidently not operate in parallel with a compound generator. Reversed polarity must, therefore, be remedied by reversing the residual magnetism, leaving all connections normal.

If the polarity is correct, let us imagine we have brought machine No. 2 up to the same voltage as the bus-bars and have then closed switches N_2 and P_2; using the information gained in the last experiment, we strengthen the shunt field of machine No. 2, expecting it then to take its share of the load. Let us suppose the equality of load division has been effected, and study the action of the two machines; it will now be shown that they are in unstable equilibrium. Suppose that the speed of generator No. 1 were momentarily raised and its generated voltage thereby raised for an instant; immediately generator No. 1 would take a slightly greater load, depriving No. 2 of some. The increased current flowing through the series field of machine No. 1 would further increase its generated voltage while that of No. 2 would be decreased. This action is likely to continue until all of the load current is being supplied by generator No. 1 and none by No. 2, and it is also likely that the generated voltage of No. 2 will drop below the voltage of the bus-bars, so that this machine takes current and operates as a motor. This follows from Eq. (2).

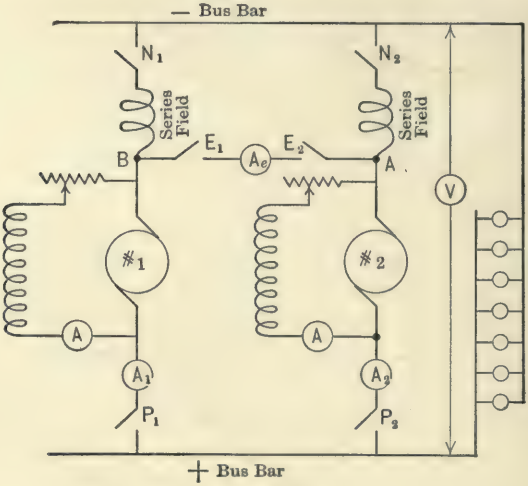
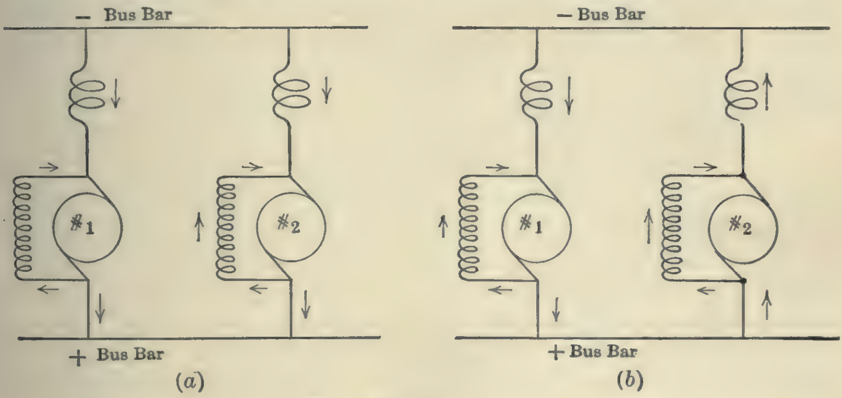


FIG. 20.

In the case of shunt generators operating in parallel, no danger results if one of the machines operates as a motor. In the case of compound-wound generators, this action is dangerous, with the condition of no equalizer connection assumed. In Fig. 21a are shown two compound-wound generators operating in parallel, both machines acting as generators. The directions of the currents flowing through the shunt fields and through the series fields are shown by arrows.

As the machines are cumulatively-wound compound generators, the m.m.f.'s of the shunt and series fields are added. When machine No. 2 operates as a motor, as indicated in Fig. 21*b*, the current through its armature and series field reverses, while the direction of its shunt-field current remains the same as before. The m.m.f. of the series field now opposes that of the shunt field and results in a reduction of the net flux of the machine.

A motor, the field of which is weakened, tends to increase its speed. This, however, is difficult in the case assumed, since the generator then tends to drive its prime mover; it is generally able to accelerate the latter but little. If the speed cannot rise appreciably the result of a weakened field is an actual decrease in generated e.m.f., or, as the machine is operating as a motor, a decrease in c.e.m.f. The action is cumulative; if the c.e.m.f. is decreased, more current flows through the armature and series field, further strengthening the series field and further decreasing the net flux. Thus, the more current the machine takes, the more the field is weakened; the more the field is weakened, the more current flows through its armature and series field. This goes on so rapidly that the speed has no chance to increase enough to keep the c.e.m.f. up to normal, and the result is that machine No. 2 forms a short circuit for No. 1. Meanwhile, all fuses and circuit breakers in the local circuit will have blown. The inrush of current into machine No. 2 will often be so great as to cause the series field to overpower the shunt field and actually reverse the polarity of the residual magnetism of generator No. 2.



(*a*) (*b*)

FIG. 21.

To prevent the action described and make the operation of compound-wound generators in parallel stable, a connection, $E_1 - E_2$

(Fig. 20), called the equalizer bus, is employed; it joins together the two generators between their series fields and armatures, and prevents reversal of current through the series field of the machine operating as a motor. Suppose that switches E_1 and E_2 are closed and that machine No. 2 is operating as a motor. Its armature current would then flow from the positive bus-bar through the armature to the point A, where it has the choice of continuing on through the series field (No. 2), along the negative bus-bar and through the series field of generator No. 1, or, flowing directly over the equalizer bus to the point B. In practice the cross-section of the equalizer bus is the same as that of the main bus-bars. The resistance of the path through the two series fields and the negative bus is therefore relatively high as compared to the resistance of the equalizer connection alone; the armature current of the machine operating as a motor will therefore practically all of it flow directly over the equalizer bus. Machine No. 2 is thus practically operating as a shunt motor, which action is not attended by any dangerous conditions.

The resistance of the equalizer bus being very low, the IR drop across the two series fields must be equal under all conditions. If the load of No. 2 increases for any reason, the IR drop across its series field tends to increase; this can only increase if a corresponding increase in the drop across the series field of generator No. 2 takes place. This means that more current must flow through the series field of No. 2. Thus, if No. 1 generator tends to increase its share of the current output and so to raise its generated voltage, some of the increase in current must flow over the equalizer connection through the series field of No. 2 machine, thereby raising the generated voltage of the latter. The division of the load between the two generators thus tends to remain constant.

It follows from the above that the series-field resistances must be inversely proportional to the rated full-load current outputs of the generators. If this is not the case, the series-field currents will not be of the proper values when the armature currents are correct. Machines intended for parallel operation must also have not only the same degree of compounding, but also the same shaped compound characteristics. Machines with different characteristics will not share the load equally at all loads from no load to full load.

The sequence of switching in putting machines on or off the bus-bars is important. Consider that generator No. 1 is connected to the bus-bars and is supplying load. To parallel generator No. 2 it is first brought up to rated speed, and then switches N_2 and E_2 are closed (E_1 is supposed already closed). The machine is then brought up to the bus-bar voltage by shunt-field regulation, and switch P_2 closed. If the voltage of the incoming generator is brought up to the bus-bar voltage before closing switches N_2 and E_2, a little further voltage adjustment will be necessary after these switches are finally closed. In any case switch P_2 must not be closed unless the generator is up to voltage, and must always be the last one in. Load is then put on machine No. 2 by strengthening its shunt field. If a machine is to be taken off the bus-bars, its load is first reduced to zero by weakening its shunt field and switch P_2 opened first. After that, switches E_2 and N_2 may be opened in any order.

Procedure.—Start one machine, bring it up to rated speed and voltage and put about half-rated load upon it. Bring the other machine up to proper speed and voltage, test for polarity, and following the ideas given in the theory above, connect it in parallel with the other. Practice transferring the load from one machine to the other, and disconnecting each machine in turn from the bus-bars. Cause one machine to operate as a motor and note results.

	Generator No. 1					Generator No. 2				System	
1	2	3	4	5	6	7	8	9	10	11	12
Bus-bar Voltage	External Current	Shunt-Field Current	Kw. Output	Speed	Equalizing Current	External Current	Shunt-Field Current	Kw. Output	Speed	Load Current	Kw. Output

Make two tests, taking readings at about eight points in each run as follows and recording readings in a log as suggested in the above table.

(*a*) Start with the generators connected in parallel, but with no load upon either, and gradually increase the load up to about 25 per cent overload, keeping the system voltage and speeds constant at rated values and the current equally divided between the two generators.

(*b*) Start as before and add load, keeping only the speeds of the machines constant. Allow system voltage to vary and the load to divide as it will.

After the second run, with half-rated load on each generator, note the effect of shifting brushes. Do not shift the brushes too far, especially if the machines are equipped with commutating poles.

Curves.—Plot three curves (one for run *a* and two for run *b*) between system voltage and individual external currents (abscissae).

Questions.—

1. What is likely to happen if compound-wound generators are operated in parallel without an equalizer connection?

2. What are the functions of the equalizer bus and how does it carry them out?

3. What is the sequence of switching in connecting and disconnecting a generator from the bus-bars, and why is this sequence necessary?

4. If, with the machines connected as in Fig. 20, test indicates that the polarity of the incoming machine is opposite to that of the bus-bars, what must be done and why?

5. In a station, how would the operator know if one generator had, through some maladjustment, become of a motor?

6. What would be the effect on the operation of two compound generators, normally in proper adjustment for proper parallel operation of (*a*) poor contact in switch N_2 of Fig. 20; (*b*) poor contact in switch E_2, (*c*) poor contact in switch N_1?

7. Is the parallel operation of compound generators entirely satisfactory?

XI. COMMUTATING-POLE MACHINES

Object.—Study of the action of the commutating-pole motor and generator. Effect of brush position.

Theory Involved.—As the necessity for commutating poles on certain machines has been thoroughly discussed in the text of Volume I, only a review of the question will be given here.

The current in any coil of a revolving armature must be reversed in direction as the coil moves from one side of a brush to the other; if the reversal is completely brought about before the coil-ends, connected to certain adjacent commutator bars, have moved from under the brush, the commutation is sparkless and satisfactory. But if, as the mica insulation between the two bars, to which the coil in question is connected, moves under the trailing brush tip, the current is not yet completely reversed, then sparking is sure to take place here and the commutator and brush will deteriorate. In order to bring about the proper reversal of the current in the commutated coil, the brushes are shifted so that the short-circuited coil is acted upon by the fringe of the field at the proper pole tip, or else the machine is provided with commutating poles, the function of which is to provide the flux required for sparkless commutation.

With the brushes of a commutating-pole machine in their proper position, the e.m.f. generated in the conductors moving under the commutating poles has no effect on the c.e.m.f. of a motor, or the generated e.m.f. of a generator; that is, the flux directly under the commutating poles of a machine has no effect on the speed or torque, if it is a motor, or upon the external characteristic, if it is a generator. With the brushes symmetrically placed with respect to the center line of the commutating poles, whatever voltage is generated in one path of a winding by one commutating pole is exactly neutralized by the other.

This neutralization of effect is at once destroyed if the brushes of a commutating-pole machine are shifted at all from their proper position, or if the brushes are improperly placed, and the operation of the machine is very seriously affected. Not only is the commutation likely to be imperfect, but the operating characteristics, torque, speed, external characteristics, etc., change very materially.

While theoretically the flux for a commutating pole divides equally between the adjacent main poles for its return path, thus strengthening one pole and weakening the other to an equal extent, this balance in effect does not occur in actual machines. Owing to the variable permeability of the iron of the magnetic circuit there is a net effect of the commutating poles on the main poles which results in a strengthening of the latter. This is shown decidedly by the slope of the external characteristic curves of a generator equipped with commutating poles, if the machine is used with the poles first connected in circuit and then disconnected. Even though the brushes are exactly in the neutral position, it will be found that the external characteristic obtained with the commutating-pole winding is considerably above that obtained without the commutating-pole winding.

The use of commutating poles has been particularly developed for motors used in machine drives. Here there must be available a large variation in speed, obtained in the older shops and factories by suitable cone pulleys, requiring belt shifting for each speed change. The motor drive, using a commutating-pole motor, permits speed changes in the motor of one to six, by merely shifting the proper lever. This lever controls the amount of resistance in the shunt-field circuit and it is the change in field strength that makes feasible the adjustable speed motor. Such motors are generally equipped with specially constructed starting rheostats, having the field resistance mounted in the same box as the starting resistance.

A type of starting rheostat for an adjustable speed motor is shown in Fig. 22. It is equipped with three arms, *A*, *B*, and *C*. Arms *A* and *B* are pivoted at *P* and are so arranged that arm *B* moves under arm *A*. A small peg, *E*, inserted into arm *B*, prevents arm *A* from moving past arm *B* to the right; if arm *B* moves to the left, it will force arm *A* to also move to the left. A spiral spring at the pivot *P* acts to force arm *B* to the left and therefore also arm *A*, by reason of peg *E*; in the " off " position (shown in solid lines), both arms *A* and *B* are held against a stop *D*. Arm *C* consists of a copper contact to which a finger *F*, is attached as shown; a spiral spring at the pivot *Q* holds arm *C* to the right against the stop *G*.

When arm *A* is grasped by the handle *H* and moved to the right it pushes arm *B* before it, overcoming the tension of the spiral spring at *P*. As arm *A* reaches the end of its travel, a second peg *N*, inserted on the under side of arm *B*, engages the finger *F* on arm *C*, forcing arm *C* to move down to the left so that arm *C* passes from contact *J* to contact *K*. At the end of its travel, arm *B* comes in contact with the no-voltage release magnet, which holds arm *B* in the running position (shown as *B*′, by dotted lines). As there is no spring pressure

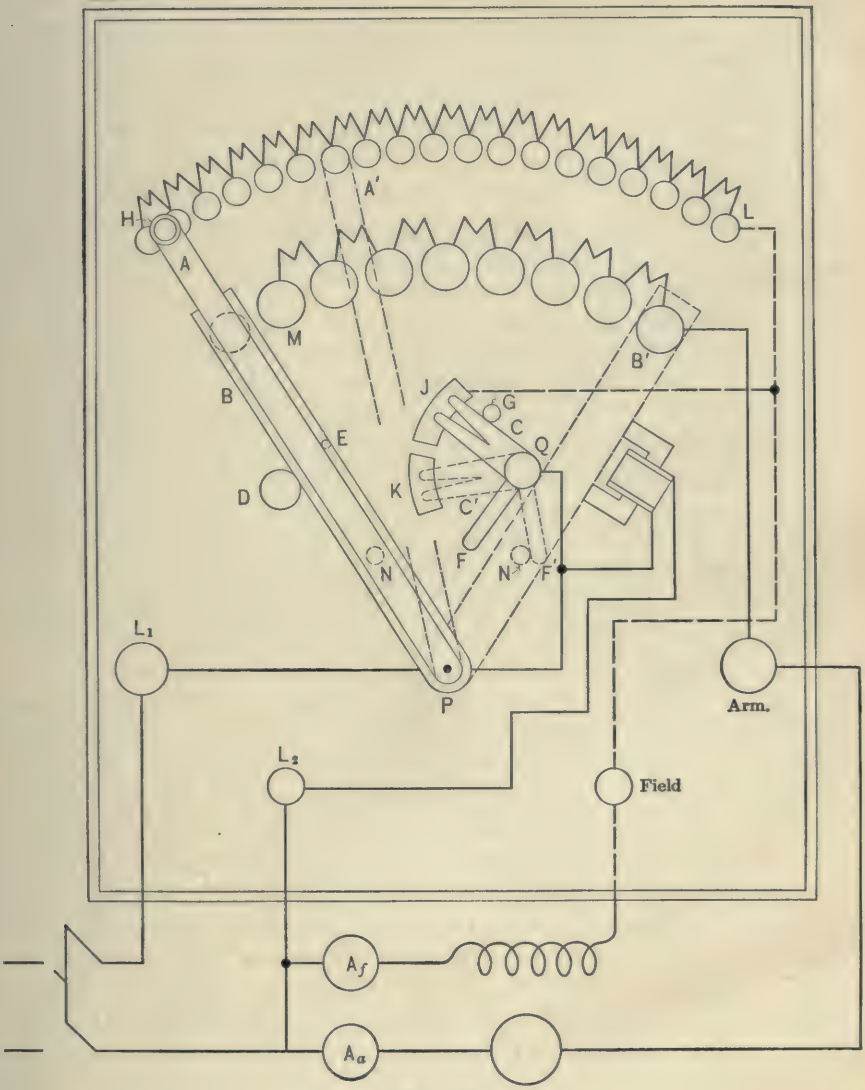


Fig. 22.

acting directly on arm *A*, it may now be moved backward and will remain wherever left.

When the main switch is closed, the shunt-field circuit is made, current flowing (broken lines) in at terminal L_1, to pivot *P*, pivot *Q*, over arm *C* to contact *J*, and then to the field. As arm *B* is forced in turn to the right by arm *A* (the handle *H* of which the operator is holding), armature current flows from pivot *P*, to button *M*, through all the starting resistance to the armature; the motor, having full field strength, starts to rotate. As the arm *B* moves further to the right, the resistance in series with the armature is gradually cut out. When, at the end of its travel, arm *B* pushes arm *C* down to the left, the contact between arm *C* and contact *J* is broken; arm *A* is then over button *L*. Field current is now compelled to flow from pivot *P*, over arm *A*, button *L*, to the field. As arm *A* is moved backward to the left, resistance is inserted into the field, and the motor speeds up.

Procedure.—If the experiment is to be performed on a compound-wound generator, determine its compound characteristic with its brushes in the proper position and also for a backward and a forward shift of the brushes; determine its external characteristic as a shunt generator with the brushes in the proper position and also with them shifted backwards. Consult the instructor as to the amount the brushes are to be shifted. Also determine the external characteristic as a shunt generator with the brushes in the proper position, without using the commutating-field winding.

If the experiment is to be performed on an adjustable speed motor, operate it with the commutating-field winding properly connected and also with it reversed; this is to be done at a fairly high speed with about full load. With the brushes properly set and the commutating field correctly connected, make a brake test at the lowest speed for which the machine was designed, taking all data necessary to obtain its speed-load characteristic and efficiency. Repeat the same procedure, starting at an intermediate speed, and, in a third run, at the highest speed for which the machine was designed. Make a fourth run with the brushes shifted forward by the instructor, starting at the same intermediate speed as in the second run. Have the brushes shifted backward by the instructor, and make a fifth run, starting again as in the second run. Repeat the second run without using the commutating-field winding.

Caution.—Because of the possible danger that the motor may run away, particularly when the brushes are shifted backwards, it is advisable that each student know how to quickly shut the machine down before it has time to damage itself.

Curves.—If the experiment was performed on a generator, plot on one sheet the external characteristics determined. If performed on a motor, plot on one sheet of cross-section paper the curves of efficiency, speed, and torque against horsepower output, from the results of the first, second and third runs. On a second sheet plot curves between speed and horsepower output from the results of the third, fourth, fifth and sixth runs.

Questions.—

1. Explain how commutating poles improve commutation.
2. What is the result if the commutating-pole winding is incorrectly connected?
3. What happens if the brushes of a commutating-pole machine are shifted from their proper position?
4. What is the least number of commutating poles that an eight-pole motor may have, and why?
5. If, in the parallel operation of generators equipped with commutating poles, one machine operates as a motor, is its commutating field properly connected for motor operation? Why?
6. For what types of service are adjustable-speed motors adapted?
7. Do commutating poles neutralize armature reaction? Explain.
8. Give a possible explanation of the difference in the slope of the external characteristic when using commutating-pole windings and when not using them.

XII. LOCATION AND REPAIR OF FAULTS

Object.—Methods for locating and repairing faults in continuous-current motors or generators, in so far as these faults are caused by open coil in the armature, short-circuited coil or turn on the armature, grounded field or armature winding.

Theory Involved.—An electric motor or generator consists essentially of two electric circuits mounted on an iron magnetic circuit, but well insulated therefrom. The field circuit consists of a few coils mounted on stationary pole pieces, and seldom gives trouble due to failure. It may, of course, become open for some reason, but a test with a dry cell and voltmeter, or an incandescent lamp on a 110-volt line, will at once detect the open circuit. It will also be shown in the case of a motor by the absence of starting torque, and the poles, when tested by a bunch of iron keys or a similar object, will be found not magnetized. The winding may not be open but may be electrically connected to the iron poles or yoke through defective insulation somewhere; where the end of a coil comes through a metallic end piece, the insulation may chafe and finally wear through as a result of vibration of the machine, or the joint of the ends of two neighboring coils may be pushed out of place and may be touching the yoke of the machine, resulting in a " grounded " winding.

A grounded field circuit will generally have no effect on the actual operation of the machine, as a ground in the winding in one point does not permit a flow of current; if, however, another ground develops somewhere else in the field or armature circuit, a path is established and danger is likely to ensue. If two grounds occur in a field winding, that part of the winding between the two grounds is short-circuited and so the magnetic circuit is not properly excited. In the case of a multipolar generator this may result in a bad short-circuit condition in the armature, and in any case, no matter how many poles the machine may have, the generated voltage will be much less than it should be. If the machine with two grounds in its field circuit is a motor, the torque developed will be lower than normal, excessive current will flow in the armature circuit, and the motor is likely to run away and endanger itself by the excessive centrifugal forces set up.

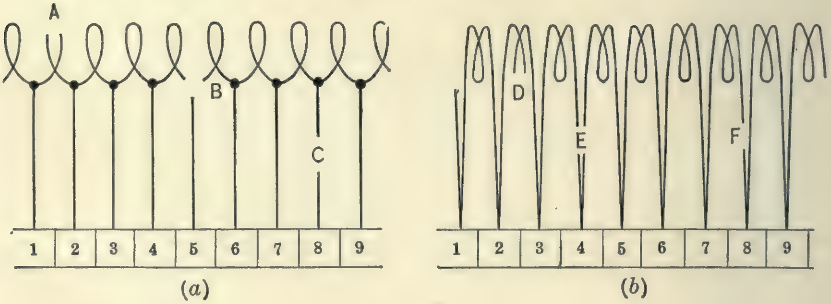
The armature circuit is much more complex in construction than the field, and is therefore much more likely to develop defects. One or more grounds may occur where the sharp edges of the laminae have cut through the coil insulation, or the end connections may make contact with the armature spider, etc. One coil may be open-circuited, either somewhere in the coil itself or in the end connections going to the commutator. The coil itself may not be open, but its connections may pull loose from the commutator bars to which it should be fastened. Either the whole, or part, of a coil, or several coils, may be short-cuited. The end connections of armature coils are always bent to cross each other, and designed to fit snugly together, and frequently have to be hammered into the right places, so that there is a good chance of trouble developing on the end of the armature connected to the commutator. The manifestation of these faults will generally be either increased sparking at the commutator or excessive heating of certain parts of the armature winding, or possibly both together.

The location of the various faults is generally very simple; if the trouble is an open circuit, some current-indicating instrument will locate it, unless there are several paths in parallel; a voltmeter indication then shows abnormally high voltage across the break compared to the drop in other parts of the same winding. Grounds are first detected by seeing if current will flow from the winding to the frame and are located by the potential difference between the winding and the frame; at the grounded point there will be no potential difference, no matter how much current is flowing through the winding.

A megger (see Section 111, Volume I) enables the operator to easily measure the insulation resistance of a machine; grounds should be detected by the regular megger tests. As the insulation gets thin, or dirt accumulates, either of which effects may result in a ground if continued, the insulation resistance will continually decrease and so warn of impending trouble.

The way in which open circuits in an armature may occur is suggested in Fig. 23. In large machines, separate commutator risers are employed; they are connected to the bars of the armature winding at its outer periphery, as indicated in Fig. 23*a*. In smaller machines, the ends of the coils composing the winding are themselves carried down into the commutator bars as in Fig. 23*b*. In the type indicated in Fig. 23*a*, the winding may open up in any one of three ways. The winding itself may open up, say, at the back of the armature, as indicated as in *A*, a break may occur which both opens the winding proper and completely disconnects it from the commutator riser, as in *B*, or a break in a commutator riser only may occur, as in *C*.

In cases *A* and *B* sparking will result. In a bipolar machine, when the break in the winding lies between brushes, current will flow from brush to brush around the other, or good, armature circuit; but when the break passes under a brush and is thus transferred to the other side of the armature, a spark results, due to the rupture of the current and the self-induction of the winding. The spark will therefore only occur when bar 2 and the brush separate (Case *A*), or bar 6 and the brush part company (Case *B*); these bars, therefore, blacken and pit. Break *C* will generally show no decided symptoms if the brushes are wide enough to cover more than one commutator bar, as is generally the case. If the brushes used are so narrow as not to span more than one commutator bar, sparking will result; when the brush is entirely over bar 8, no current can enter or leave the armature. Should the broken end of the riser attached to the winding come in contact with the risers on either side, a short-circuited coil results; this fault will be considered further on.



(*a*) (*b*)

Fig. 23.

A simple way of locating an open armature coil (Case *A*) if no commutator bar shows decided blackening is to connect a few dry cells across the brushes. The leads from a voltmeter of the proper range are then touched successively to adjoining commutator bars. When connected across adjoining commutator bars on the good side of the armature, the voltmeter will read only the normal *IR* drop across each good coil, but on the side where the armature is open, since no current is flowing through it, the entire voltage of the dry cells will be found across the bars between which the armature circuit is open. In Case *B* it is necessary to span bars 4 and 6, the reading from bar 5 to either bars 4 or 6 being zero.

The proper remedy for an open coil is generally to replace it with a new one. If time does not permit, or a new coil is not available, the break may be closed by splicing in a piece of wire. Temporary repairs may be effected, however, by electrically connecting bars 1 and 2, Case *A*, or bars 4, 5, 6, Case *B*, by soldering them together or connecting them by a copper strap held by screws tapped into the bars. The latter method of repairs should only be employed where it is absolutely necessary to keep a machine in operation; proper repairs should be made at the first opportunity.

A short-circuited coil in either a motor or a generator will, as it rotates, cut the field flux and therefore generate voltage. This voltage will cause current to circulate within the short-circuited portion of the coil, and since the resistance of the coil is low, the current set up will be excessive. If left flowing for any length of time the excessive current will heat up the coil and ultimately burn it out, the heated insulation giving off a characteristic bad odor. The odor is often the first indication of trouble.

The short-circuited coil is often easily located by feeling the armature all over, particularly at the rear, after the machine has been operated for a few minutes. It may also be located by connecting a few dry cells across the brushes and testing with a voltmeter, as for an open coil. The resistance of a short-circuited coil being less than that of a normal coil the voltmeter reading across the bars where the short-circuited coil is connected will be less than that across the other bars.

If the short circuit in the armature is not due to solder or copper dust between commutator bars or risers the trouble must lie within the coil itself. In this case it is best to put in a new coil. A short-circuited armature may be temporarily repaired by opening the short-circuited coil and then bridging the commutator as for an open coil.

To locate the exact coil in an armature which is grounded, a few dry cells in series with a buzzer are joined across the brushes, as in Fig. 24. One end of a telephone receiver is permanently grounded to the frame of the machine; its other end is free. The ground to be located is indicated by *G*. The free end of the telephone is now touched successively to the commutator bars; suppose for the moment that it is touched to bar 6. In the circuit consisting of the telephone and the two grounds the pulsating difference of potential, or IR drop, across the coils between commutator bars 6 to 10 is impressed and a sound is heard in the telephone. When the telephone lead is touched to the bar at which the ground is located there is no voltage impressed on the telephone circuit and no sound is heard in the telephone. However, with the armature in the position shown in Fig. 24, it will be found that when the telephone lead is touched to bar 16 no sound will be heard in the telephone. We shall call this apparent ground the *phantom ground*. The reason for its apparent existence is that the IR drop in the coils between bars 10 to 13 is equal *and opposite* to the *IR* drop in the coils between bars 13 to 16.

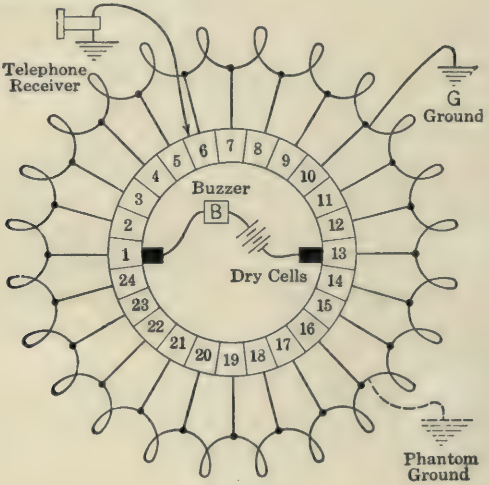


FIG. 24.

In making this test on a two-path armature winding, therefore, two commutator bars will be found at which the telephone is silent; one of these is the real ground and the other is the phantom ground. In order to distinguish between them the armature is rotated a few degrees, as in Fig. 25. The real ground must appear at the same place, but the

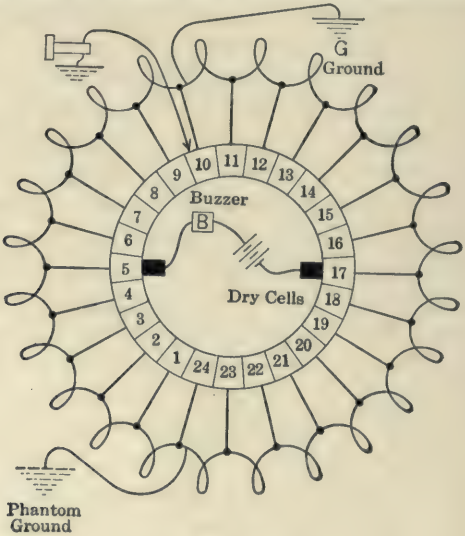


FIG. 25.

phantom ground will be found elsewhere. In fact it will rotate the same number of degrees that the armature is moved, but *in the opposite direction.*

If a multipolar armature is to be tested for a ground it is advisable to convert it into a two-circuit armature by raising such brushes that the armature circuit has only two paths, of equal resistance.

The buzzer may be omitted in this test, in which case it is necessary to continuously tap the telephone lead to the commutator bars. The telephone will sound each time the circuit is made. A voltmeter may also be used in place of the telephone, as shown in Fig. 351, Volume I. In this figure the brushes left on the commutator are not diametrical, as suggested above, and the test carried out in this way will not be quite as accurate as though diametrical brushes were used.

Procedure.—Operate the machine assigned as a motor with its field circuit separately excited and a lamp board in series with its armature. With a comparatively weak field, add enough lamps in the board to cause the armature to rotate slowly. If sparking occurs, stop the machine and locate the open coil by the method given above. If an open coil is found, bridge the commutator bars across which it occurs (it may be advisable to consult the instructor before doing this). Again operate the machine for a few minutes and search for a short-circuited coil. If one coil has heated more than the rest, verify the fact that it is short-circuited by test with a voltmeter. Then test the fields and armature for grounds and, if the armature is found to be grounded, locate the exact coil at which the ground is located.

Questions.—

1. What is meant by a ground? By an open coil? By a short-circuited coil?
2. What symptoms do these faults show?
3. How can they be remedied?
4. Explain the presence of a phantom ground.

XIII. THE LEAD STORAGE BATTERY

Object.—A study of the characteristics of the lead storage battery.

Theory Involved.—The construction and general characteristics of the two commercial types of storage batteries, the lead cell and the Edison cell, were analyzed in Chapter XII, Volume I. This material should be carefully read over before carrying out the tests suggested below.

The condition of charge or discharge of a battery cannot be determined by reading its voltage on open circuit; neither will a hydrometer reading of the density of the electrolyte tell how much charge there is in the cell. A voltmeter may read over 2 volts on a bad cell, not being used, and as soon as load is connected, drawing appreciable current, the voltage may drop several tenths of a volt; such behavior indicates a nearly discharged cell.

The density of electrolyte cannot serve as a measure of the cell's condition unless the density of the cell in the discharged condition is known. If the specific gravity is 0.100 higher than the value in the discharged condition the cell is probably completely charged. The average lead cell will have a density of electrolyte between 1.23 and 1.30 in the charged condition.

Whereas it is not good practice to charge and discharge storage batteries (especially lead cells) at high rates, in this test it is necessary to do so as the time available in the laboratory period does not permit charging at the proper rate. The limiting voltage and ampere-hour efficiency which may be expected at these high rates of charge and discharge were given in Chapter XII, Volume I.

Procedure.—The connections to be used in this test are shown in Fig. 26. With the switch thrown to the left the cell may be discharged through the adjustable resistance R; it is preferably a carbon plate rheostat. With the switch thrown to the right the cell may be charged, the amount of current being adjusted by the number of lamps in circuit and the adjustable resistance, J.

Two cells are to be tested, one under charge and the other under discharge. Connect up the cell to be charged as in Fig. 26, omitting the discharge resistance R. Charge the cell at about a two-and-one-half-hour rate, maintaining this rate by means of the adjustable resistance in the supply. Take readings of open- and closed-circuit voltage, density by hydrometer, and temperature by thermometer, every three minutes for the first fifteen minutes, or until conditions become steady. After that, readings may be taken at longer intervals until near the end of the test, when, conditions changing rapidly again, three-minute readings must again be taken. Continue the charge until the terminal voltage and density remain constant for several readings.

After the first cell has been on charge for ten to fifteen minutes, start the second cell on discharge at its two-hour rate, maintaining this rate by means of the adjustable rheostat, *R*. Take the same readings at similar intervals as for the cell on charge. Continue discharging the cell until its open-circuit voltage falls to a value as determined from Eq. (124), Volume I.

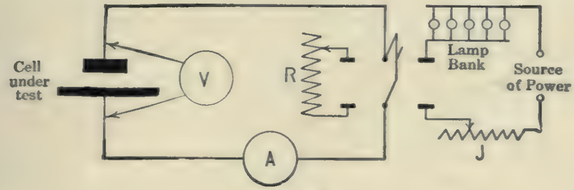


FIG. 26.

Curves.—Plot the results for each cell on a separate sheet of cross-section paper. Plot elapsed time as abscissas against open- and closed-circuit voltage, density, temperature and resistance. The resistance of a cell is determined by dividing the difference between its open- and closed-circuit voltages, by the current.

Questions.—

1. Why does the voltage of a cell fall on discharge? Why does it rise on charge?
2. Why should a lead cell not be completely discharged?
3. What factors influence the life of a lead cell?
4. Explain the form of the curves obtained.
5. A battery is to be made up of cells such as you tested to furnish 200 amperes at 135 volts. How many cells would you use, and how would you arrange them?

XIV. THE WATT-HOUR METER

Object.—Study of the watt-hour meter and its adjustments.

Theory Involved.—The theory of both the Thomson type of watt-hour meter and the mercury flotation type has been so well analyzed in the text that it is not worth while repeating here. The student is to read over carefully the material given in Chapter VI, Volume I, dealing with the type of meter to be tested, before trying to carry out the tests outlined below.

Procedure.—Measure the resistance of both circuits of the meter assigned for test. The current circuit will, of course, have a very low resistance and will require a very low-reading voltmeter to read the drop across it even when carrying full-load current. It will do no harm to the meter if 100 per cent overload current is passed through it for the short time required for making this measurement. For measuring the potential circuit a Wheatstone bridge may be used, or a low-range ammeter may be used to read the current through it when the rated voltage is impressed on the circuit. A low-resistance voltmeter makes a very convenient ammeter for this measurement, if its resistance is known. A voltmeter having a full-scale reading of 5 volts, for example, and having a resistance of 400 ohms (a likely figure) takes a current of 0.0125 ampere for full-scale reading. This figure then serves to change the volt scale into a current scale.

Measure the current through the potential circuit with rated impressed voltage, both when the meter is standing still and when it is rotating at full speed, to see if the c.e.m.f of the armature has any appreciable effect on the amount of current taken by this circuit.

Make connections to the meter, as shown in Fig. 27, the ammeter and variable load (lamp bank is convenient) with a capacity 50 per cent greater than the rated load of the meter.

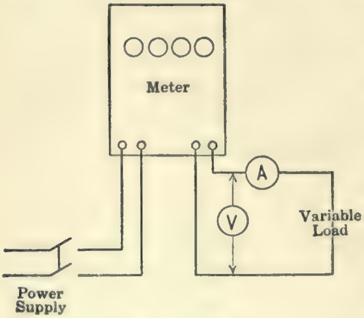


Fig. 27.

Note whether the meter creeps, when carrying no load; if it does, get the time of one revolution.

Leaving the meter as found, determine its accuracy at 10 per cent, 50 per cent, and 100 per cent rated load, taking the time of such a number of revolutions that the time required is about one minute. Take several readings for each setting until three check one another within plus or minus 1 per cent.

Reduce the load to 10 per cent of rated load and, by means of the light-load adjustment, bring the meter to within 2 per cent of being accurate; carry out the same procedure for full load. Check the light-load reading, to see if the full-load adjustment has affected its accuracy.

Take readings at 10, 25, 50, 75, 100, and 150 per cent rated full-load current, so that a calibration curve of the meter may be plotted.

A suitable log form for recording the readings is shown herewith.

Make and type of meter.................. Manufacturer's meter number......
Rated amperes........... Rated volts........
Rate of creep............ Revolutions in........minutes........seconds.
Disc constant K......... Testing constant $K_t = K \times 3600 =$ ....

Amperes	Volts	Watts	Per Cent Rated Load	Revolutions R	Seconds S	Watts $W=\frac{K_t\times R}{S}$	Per Cent Regulation $=100\times\frac{W}{C}$

Curves.—Plot a curve between per cent registration, as ordinates, and per cent load, from the results obtained after the meter was adjusted at both light and full loads.

Questions.—

1. What characteristics should a watt-hour meter possess?
2. Why are both light-load and full-load adjustments necessary?
3. Which is the more important adjustment, commercially? Why?
4. What would be the probable effect of dust, fumes, and vermin, getting into a meter, and what kind of a cover should a meter therefore have?

5. What seem to you to be the advantages and disadvantages of the two types of meters described in the text?

6. As the meter is ordinarily connected in service (see Figs. 123 and 125 of Volume I), who is charged with the losses occurring in the meter?

7. If the meter you tested had any creep at the start of the test, calculate what this amount would cost the customer per day, at 10 cents per kilowatt hour.

8. Knowing the accuracy with which you were able to make the measurements, calculate the maximum value that the counter e.m.f. of the armature of the meter, revolving at full speed, could have reached.

9. Obtain from the instructor the number of turns in the armature of the meter, as well as the number of turns in the field coils; treat the two field coils as a single solenoid of the same over-all length, as the distance over them, as they are in the meter, and calculate the value of c.e.m.f. generated, for comparison with your answer to question 8.

10. What would be the effect on the calibration curve of a meter of a combination of dirty commutator, roughened jewel and pivot, and weakened magnets?

11. What is the power used in the meter you tested, at light load? At full load?

ALTERNATING-CURRENT EXPERIMENTS

ALTERNATING-CURRENT EXPERIMENTS

I. WAVE SHAPE, EFFECTIVE VALUES, POWER AND POWER FACTOR

Object.—To determine the wave form of an alternator and to determine its effective value for comparison with the reading of an alternating-current meter. To plot curves of voltage and current in an inductive circuit, and from the curves to calculate power and power factor for comparison with readings of a wattmeter.

Theory Involved.—Practically all a.c. theory is worked out on the assumption that the generators supplying the power generate a pure sine wave of voltage. Such is actually far from the fact; a machine must be specially designed and built if it is to give a voltage wave form which does not differ, we will say, more than 1 per cent from a sine-wave shape. The ordinary salient-pole machine gives a voltage wave which may differ as much as 10 per cent from a true sine wave.

Two general forms of wave distortion are encountered in practice, these being indicated in Fig. 1. In curve *a* of this figure the general shape of the wave is sinusoidal; in the dashed line a pure sine wave has been passed as nearly as possible through this curve, and it is seen that the residual (by which the actual curve differs from a sine wave) is made up of small ripples, which themselves are nearly sine waves of

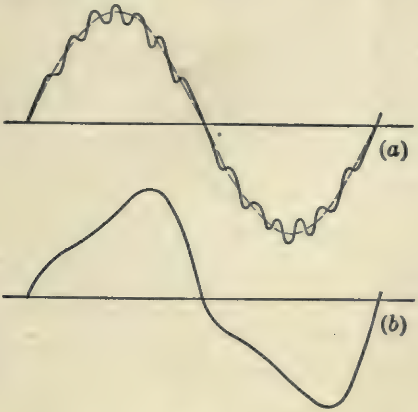


FIG. 1.

a frequency much higher than the fundamental frequency of the alternator. These ripples are due to the teeth and slots on the armature core, and will be most pronounced on short air-gap machines; their frequency depends upon the number of teeth per pair of poles, etc.

The actual ripple is always made up of two high-frequency voltages differing from one another in frequency by twice the frequency for which the alternator is built. If a 60-cycle alternator has 12 slots per pair of poles (i.e., 24 armature slots for a four-pole, 1800-r.p.m. machine) the ripple will be due to the eleventh and thirteenth harmonics of 60 cycles, i.e., 660 cycles and 780 cycles. The presence of both of these frequencies results in a kind of " beat " appearance, the actual ripple being much more marked in some parts of the voltage wave than in others.

In the second kind of distortion the wave may be more smooth, but its shape may differ materially from the shape of a sine wave; it may be too peaked (Fig. 8*b*, Volume II), too flat (Fig. 8*a*, Volume II), or it may be lop-sided, as shown in curve *b* of Fig. 1. This latter kind of distortion, if in the shape of an e.m.f. wave, may be due to the fact that the armature reaction of the machine has concentrated most of the field flux in one side of the pole faces; if present in a current wave, the voltage impressed on the circuit being essentially sinusoidal, the peaked form is generally due to the effect of iron on the inductance of the circuit. It may occur if there is gaseous conduction, such as an arc, present in the circuit.

All alternating-current meters are calibrated in terms of the *effective value* of the voltage or current, that is, the square root of the mean square of the curve of voltage or current. It is shown in the text (Section 13, Volume II) that for a pure sine-wave form, the effective value is $\frac{1}{\sqrt{2}}$, or 0.707, of the maximum value. In the case of a distorted wave shape, the effective value is the square root of the sum of the (effective values)^2 of all the component sine curves making up the actual distorted curve. This effective value of a complex wave (which an accurate a.c. meter will read) bears no definite relation to the maximum value of the distorted wave; it may be either more or less than 0.707 of the peak value.

The power used in a single-phase alternating-current circuit depends upon the voltage impressed, the current flowing, and the angle of phase difference between the two; it varies, of course, from instant to instant (see Sections 21, et seq., Volume II); therefore, when the power of an a.c. circuit is mentioned, the *average power* is always meant. In the case of sine-wave voltage and current, the average power is equal to the product of effective volts by effective current by cosine of the angle of phase difference. In the case of distorted voltage, or current, or both, the phase difference is a fictitious quantity and cannot be measured from the curve sheet of voltage and current, even though these are accurately plotted by some means or other. For such cases the average power must be found by actually constructing the curve of instantaneous power (product of voltage and current curves), and the average value of the resultant curve must be found by getting the area and dividing by the base.

In case a wattmeter is available, however, and its calibration is known to be accurate, its reading will be the average value of the power, whatever the form of voltage and current curves and their relative phases. That is, the wattmeter actually indicates the average value of the power curve for all conditions which can be obtained in practice. By getting a wattmeter reading, and the effective voltage and current in the circuit by voltmeter and ammeter, the power factor (cos ϕ) of the circuit can be at once calculated from the relation

$$\text{Wattmeter reading} = EI \cos \phi,$$

thus obtaining cos ϕ; ϕ itself can be found from tables and the angle between voltage and current can thus be determined, on the assumption that thay are both sine waves. In case they are not (either or both) sine waves, the value of ϕ obtained from the above equation will have no significance in terms of the apparent phase difference of voltage and current curves.

It is the object in this experiment to plot the curves of voltage and of an alternating current which the voltage causes to flow in an inductive circuit, by some accurate method; also, to read by meters the voltage, current and power used in the circuit, and compare them with the values obtained from the respective curves. Voltages and currents in an a.c. circuit may be obtained by oscillograph, ondograph, or by use of the " point-by-point " method. The " point-by-point " method is more accurate than either of the others and requires less skill to operate, and so is to be used in this test.

The " point-by-point " method, or method of instantaneous contact, as it is sometimes called, will give curves which are within a fraction of one volt of the actual curve, under ordinary conditions. If desired, very much more precise results than this can be obtained, but for this test such precision is sufficient. The general idea involved in the scheme is indicated in Fig. 2. Two batteries, A and B, are connected together through a telephone receiver, as shown; if switch S is closed, current will flow through the receiver except under one condition, i.e., when the e.m.f.'s of the two batteries, A and B, are just equal and opposite. If one of the batteries has a variable voltage, it may be just equalized to that of the other by changing it until, as the switch is closed, no click is heard in the telephone. If the switch S is a rotating one, closing, say, 500 times a second, the series of clicks, occurring at regular intervals $\frac{1}{500}$ of a second apart, will give a sustained note of 500 vibrations a second, a frequency for which the ear and telephone are both sensitive. With good telephone receivers in a quiet room, a difference of 0.001 volt between the two batteries can be determined by this scheme; as the test will use a frequency much lower than 500 cycles, at which the ear and telephone are both less sensitive, and as a laboratory is a noisy place, it will probably be found that about 0.1 volt is as low as can be easily detected.

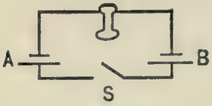


FIG. 2.

To use this method of plotting the e.m.f. wave form of an alternator we use a scheme of connections, as shown in Fig. 3. The generator I, the voltage of which is to be tested, has mounted on its shaft a disc of insulating material, E, in which a thin metal strip, F, is fitted radially, extending from a small metal drum, J, on which brush K is resting, to the edge of the disc, E. Mounted on a suitable arc on the pedestal of the machine is a brush, G, which can be moved at will over the graduated sector, H. The telephone receiver is connected in series with this disc contact (which is really a revolving switch), the alternator, I, and a portion of the resistance, AB, which latter is connected to a supply of continuous voltage.

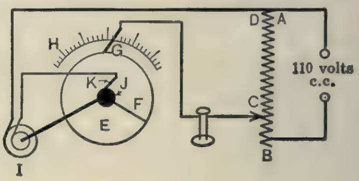


FIG. 3.

In case the alternator is a two-pole machine, only one strip, F, is used; if it is a four-pole machine, two strips 180 degrees apart are used; for a six-pole machine three strips 120 degrees apart are used. As the disc rotates synchronously with the alternator, it is evident that every time contact is made between F and G the alternator will be generating the same instantaneous value of voltage on successive cycles of the voltage wave. This idea is indicated in Fig. 4. Suppose that F and G make contact at the point a of the first cycle of voltage in Fig. 4; then as the disc and voltage values act synchronously, the circuit will also close at point a' of the next cycle, and at point a'' of the third cycle, etc. Now, by moving the contact C of Fig. 3 up and down the resistance AB, it may be possible to get a difference of potential between the points C–D which will be just equal and opposite to the value of the alternator voltage at the time the rotating switch closes. This equality may be judged by zero noise in the telephone. It may, of course, occur that the two e.m.f.'s in the circuit (the continuous one from the potentiometer, and the periodic instantaneous one from the alternator and switch) cannot be balanced with any position of contact, C, because they are not acting around the circuit, containing the telephone receiver, in opposite directions, but in the same direction. For this case the polarity of the c.c. supply to the potentiometer may be reversed, or connections C and D may be reversed. This having been done, a position for the contact C at which the telephone noise is a minimum will at once be found. (It is not generally possible to get zero noise in such a test as this.)

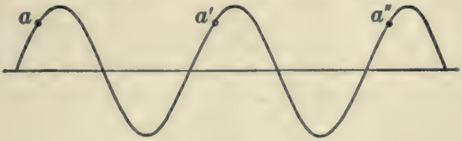


Fig. 4.

If the brush G (Fig. 3) is moved a small distance ahead of its former position the rotating switch will now close the telephone circuit at a point later in the e.m.f. cycle, hence at a point when the e.m.f. of the alternator has a different value. By sliding the potentiometer contact to another point a new balance can be obtained. By using a continuous-current voltmeter permanently connected across the points C and D of the circuit the instantaneous value of the generator voltage can be obtained for any position of brush G by reading this meter when no sound is heard in the telephone receiver. This brush G may be set at a number of equally spaced angular positions, balance obtained, and readings of the c.c. voltmeter taken at the balance points. This series of voltmeter readings, suitably plotted, will give the form of the alternator voltage.

To get the form and magnitude of a current by this scheme the current is passed through a known non-inductive resistance; the IR drop so obtained is then plotted (just as was the voltage wave of the alternator above), and from this curve, the resistance being known, the form and magnitude of the current are obtained.

In performing this test to check voltmeter, ammeter, and wattmeter, as well as to investigate the form and phase of current and voltage, it is convenient to set the apparatus up about, as shown in Fig. 5. By plugging into jack No. 1, the drop across the resistance is obtained for a given setting of the brush *G*; leaving *G* at this setting and putting the plug into jack No. 2 gives the drop across the coil; and putting it into jack No. 3 gives the impressed voltage, that is, the voltage of the alternator. If brush *G* is then shifted ahead a slight amount and another set of readings taken, and this proceeding followed, when *G* has moved 360 electrical degrees, a complete cycle of alternator voltage, drop across coil and drop across resistance, will be obtained in their proper respective phases. For a four-pole machine brush *G* should be moved 180 mechanical degrees, for an eight-pole machine 90 mechanical degrees, etc., to cover the 360 electrical degrees.

In Fig. 5 the high resistance (which should be at least ten times the telephone resistance) is to limit the amount of current which can flow; if the circuit is left badly unbalanced, enough current may flow to spoil the permanent magnet of the telephone receiver unless this high resistance prevents it. The condenser across the telephone (about one microfarad) increases very materially the intensity of sound in the telephone, thus making a more accurate balance possible. The brush *G* and strip *F* should both be very thin, so that contact is made for a very short interval of time; otherwise a poor balance will be obtained. This is due to the fact that with a wide strip and brush the contact is made for a sufficiently long time to permit the alternating voltage to change appreciably while the contact is closed. This changing voltage cannot be accurately balanced by any adjustment of the potentiometer setting.

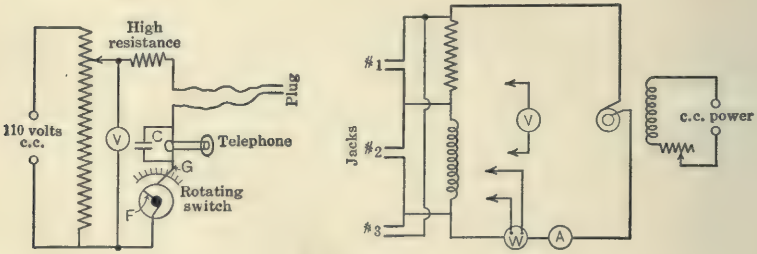


Fig. 5.

For the first curves, an inductance with an air core should be used; for this condition the current will be a practically pure sine wave. If time permits, use another coil having a closed iron magnetic path, and use sufficient current to saturate the core; for this condition the current will be much distorted even though a pure sine voltage is impressed.

Procedure.—This test should be run on a high-frequency alternator; less than 100 cycles is not advisable if accurate results are to be obtained. With a suitable air-core coil and non-inductive resistance, arrange a circuit as shown in Fig. 5; change the value of the resistance until the drop across the coil is about the same as that across the resistance. The impressed voltage must not have a maximum value in excess of the value of the continuous voltage used on the potentiometer; preferably, it is about 10 volts less.

After the correct adjustments have been made note the speed of the alternator, and read the amperes, volts, and watts, as accurately as possible, on the alternating-current meters; only this one reading of the meters is to be made, as conditions must be held constant throughout the rest of the test.

Holding the alternator speed and alternator voltage constant at the values read above, take readings of the continuous-current voltmeter for balance of all three voltages, with the brush G set at its extreme back position. Move the brush 15 degrees (electrical) forward and get another set of readings. Repeat this set of readings until a complete cycle (360 degrees electrical) has been covered. Continually note that the speed and impressed voltage are at their proper values.

If time permits, repeat the test, having substituted for the air-core inductance an iron-core one, and decreasing the non-inductive resistance, so that the drop across it is not more than about 15 per cent of the drop across the coil. Use such an iron-core coil that the voltage used in the test is sufficient to give current which saturates the iron. Determine, by continuous-current test, the value of the resistance used in the two runs; determine this at the same values of current (approximately) as were used in the test.

Curves.—Using cross-section paper, plot curves of drop across coil, drop across resistance, and impressed voltage, for the two runs (each run on a separate sheet). From the known resistances, plot the curve of current. Construct the curve of power, and by counting squares, or by planimeter, get the average height of this power curve, in watts. By measuring the distance between the zero points of voltage and current, get the phase difference between voltage and current.

From the current and voltage curves, calculate the effective value of these two quantities, and compare them with the instrument readings. See how nearly the wattmeter reading agrees with the average value of the power curve, as well as with the product of $EI \cos \phi$, E and I being the effective voltage and current, and ϕ being the angle of phase difference measured on the curve sheet.

Questions.—

1. What difficulty would be encountered in this test if the voltage across the circuit, as read on the alternating-current voltmeter, was 85 and the voltage available across the potentiometer was 105?

2. If the meter readings of a certain circuit were 60 volts, 2.5 amperes, 85 watts, how many degrees separate the curves of voltage and current?

3. What relation exists between the *instantaneous* values of voltage across each portion of a series circuit and across the whole circuit?

4. What are the essential parts of an oscillograph? (See Section 129, Volume II.)

5. For what kind of curves is the method of this test not applicable, the oscillograph being required instead?

6. The reading of an accurate alternating-current voltmeter is 77 and the voltage across the potentiometer used in this test is 110; some points on the voltage curve, however, cannot be balanced. Explain.

7. If the reading of the wattmeter is given as 500, the voltmeter as 110, and the ammeter as 7.5, could the angle between the zero points of the voltage and current curves be obtained, irrespective of the kind of circuit? Explain.

II. THE SINGLE-PHASE CIRCUIT

Object.—Study of the single-phase circuit, having inductance, capacitance, and resistance. Effect of frequency upon the various reactions. Study of effective resistance. Application of the vector diagram.

Theory Involved.—If we have a resistance, inductance, and capacitance in series, three kinds of reactions are set up when alternating current is forced through the circuit. It was shown in Chapter III, Volume II, how these three reactions, and hence the components of the impressed force which are required to overcome them, depended upon various factors, such as frequency, capacity, self-inductance, etc.

The drop across the resistance, in effective volts, is IR, where I is the effective current in amperes. Provided this resistance does not include the effects of iron losses, radiation of energy, or skin effect, this IR drop is dependent only upon the current strength. If the frequency of current flowing in the circuit is doubled, the current being maintained at a fixed value, the IR drop will be found the same at high frequency as at low frequency. The resistance itself may depend slightly upon the value of current in the circuit, because of the extra heating the conductor experiences as the current increases. For the range of current ordinarily used in the laboratory, however, the change is not appreciable, and we therefore conclude that the IR drop is proportional to current only.

In case the resistance being considered is that of an iron-core coil, as was shown in Section 52, Volume II, it differs very much from the actual conductor resistance, being augmented by the hysteresis and eddy-current losses occurring in the iron core. For such circuits the resistance can be defined only by the relation, watts = I^2R, and the R so defined is the effective resistance of the circuit. (It should be borne in mind that the effective resistance has no dependence upon the co-existing inductive reactance of the circuit; they are entirely different effects.)

Now, as the iron losses will change greatly with either frequency or flux density, it is easily appreciated that change of either current or frequency will correspondingly change the resistance of such a circuit.

In general, the resistance will increase with frequency, current being held constant, and will decrease with increase of current if the frequency is held constant.

The inductance of an air-core coil of copper wire does not change at all with current changes, nor with changes of frequency within the range possible in the average machine laboratory. The various layers of the coil act more or less like a condenser, so that actually the coil must be considered as a coil in parallel with a small condenser (the so-called distributed capacity of the coil). The effect of such a small parallel condenser is to increase the apparent inductance of the coil, the amount of this increase being nearly proportional to the increase in frequency. For the coils likely to be used in such a test as this, however, no effect of this internal capacity will be experienced until the frequency is several hundred cycles per second.

In case an iron-core coil is used, the inductance will be found to change greatly with change in current for a fixed frequency, and slightly with change in frequency as current is kept fixed. Both these effects are greater if the magnetic circuit of the coil is completely closed through iron; even a small series air gap will make the behavior of the coil (in so far as inductance of the coil is concerned) approach closely to that of an air-core coil. The variation of L of the coil with current (fixed frequency) is dependent entirely upon the variation of the permeability of the iron with various magnetic densities; the slight decrease in L with increasing frequency (current fixed) is due to the eddy currents in the iron core.

The ordinary condenser shows no change in capacity with change in impressed voltage or frequency; if the dielectric is very poor, a slight decrease in capacity may be expected with increase in frequency, but the modern telephone condenser has such a slight dieletric loss that this effect is not noticeable. What slight dielectric loss there is, added to the effects of possible leakage of current through the dielectric, and small I^2R losses in the plates of the condenser, does give a little power consumption in an ordinary condenser, and this loss, measured on a wattmeter, divided by the square of the current flowing into the condenser, gives the effective series resistance of the condenser. This resistance will generally be very small, less than 1 per cent of the reactance of the condenser.

Such series resistance must not be confused with the insulation resistance of the condenser, which is extremely high; a one microfarad condenser might have an insulation resistance of 500 megohms, for example, as measured by continuous current, but when it is tested on alternating-current supply, at 60 cycles, its series resistance obtained by ammeter and wattmeter would be only a few ohms. In general, the higher the insulation resistance of a condenser, the lower is its effective series resistance.

As outlined in Chapter III, Volume II, the single-phase circuit, having inductance, resistance, and capacitance in series (Fig. 6) requires an impressed voltage sufficient to overcome the three different reactions set up. The current in the circuit being I, and the frequency f, there is required an IR drop for the resistance, a $2\pi fLI$ drop for the inductance, and a $\frac{I}{2\pi fC}$ drop for the condenser. In case the coil is considered to have resistance, R_L (as it actually must have), the drop required by the coil is $(\sqrt{R_L^2 + \overline{2\pi fL}^2})I$, and correspondingly for a condenser having losses, a drop of $\left(\sqrt{R_c^2 + \left(\frac{1}{2\pi fC}\right)^2}\right)I.$

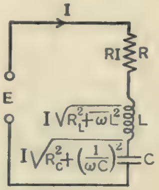

I
RI
R
E
$I\sqrt{R_L^2+\omega L^2}$
L
$I\sqrt{R_C^2+\left(\frac{1}{\omega C}\right)^2}$
C

FIG. 6.

It has been shown in the theory of the single-phase circuit that these various drops must be added vectorially to give the impressed voltage; in Fig. 7 this is indicated, the current having been taken as reference vector. Evidently the circuit will act as a coil or condenser in series with a resistance) depending upon what the frequency may be. At very low frequency the capacitance drop, $\frac{I}{2\pi fC}$, will be large enough to overbalance the $2\pi fLI$ drop, with the result that the circuit will be condensive, and the current will lead the line voltage. At very high frequency, the $\frac{I}{2\pi fC}$ drop will be low and the $2\pi fLI$ drop large, so that the circuit will act inductively.

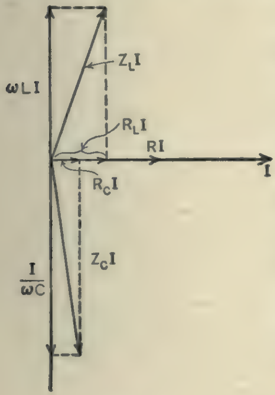


FIG. 7.

In Fig. 8 is shown the effect on a circuit, such as that given in Fig. 6, of doubling the frequency, keeping the line current constant by changing the impressed voltage as required. The circuit is assumed to have a condenser with no appreciable losses (a good telephone condenser will satisfy this requirement), and an air-core coil, which has constant resistance. In Fig. 8*a* are shown the various drops and the impressed voltage for a certain frequency, and in Fig. 8*b* are shown the same quantities for a frequency just half as great. It is seen that for the first case the line current lags behind the line voltage, so that the circuit is inductive, while in *b* the capacitance drop is twice as large as it was before, the $2\pi fLI$ drop is half as large, and the line current now leads the impressed voltage, so that the circuit is condensive.

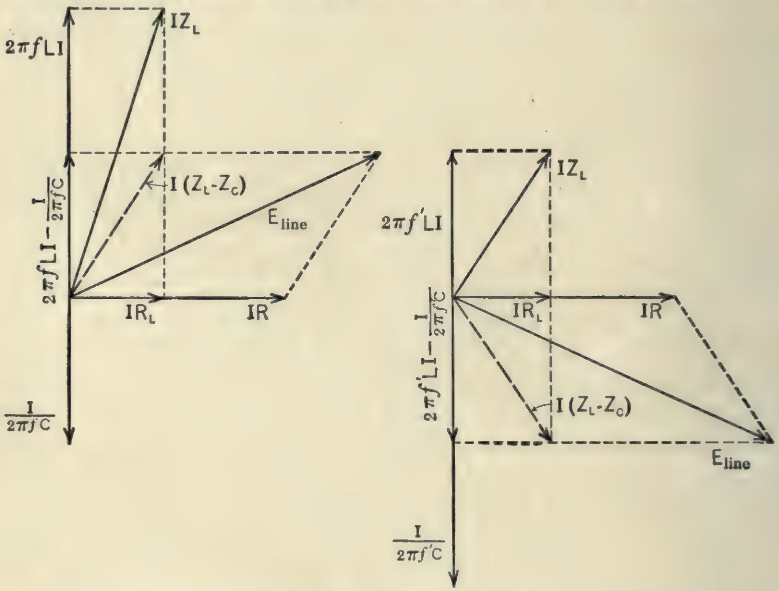


FIG. 8.

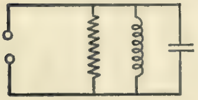


FIG. 9.

In case the various parts of the circuit are put in parallel instead of in series, as shown in Fig. 9, the line current will lag or lead according as the reactive current through the coil is greater or less than that through the condenser. To solve for the current in a parallel circuit of this kind, it is easier to lay off the three branch currents, in proper magnitude and phase, in a vector diagram, and add them to get the line current. In this diagram it is simpler to use the line voltage as the reference vector, as indicated in Fig. 10 by the phase position of I_R. Or the method of admittance, as given in Section 72, Volume II, can be used.

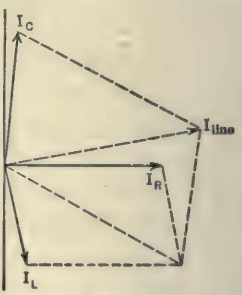


FIG. 10.

Procedure.—In carrying out the tests called for in the experiment, it is better to use a condenser of negligible series resistance, an air-core inductance coil, and some non-inductive resistance units of low temperature coefficient for the resistances called for.

Now, place the three units (resistance, coil, and condenser) in series with each other and in series with an ammeter and the current coil of a wattmeter, and connect to the a.c. power supply.

With the lowest available frequency of the machine used for power supply, adjust the coil and condenser so that the drop across the condenser is about twice that across the coil; a suitable resistance is one which gives a drop intermediate between the drop across the coil and that across the condenser. Adjust the voltage impressed on the circuit so as to get a current value well up on the scale of the ammeter, using caution not to get too high a voltage on the condensers. Read carefully the line current, voltage, and power, and then the power and voltage across each part separately. In making these measurements, some error is incurred because of the power used in the potential circuit of the wattmetter and in the voltmeter. In general, these errors will be a minimum if the following procedure is followed: When getting the total power, connect the voltmeter and potential circuit of the wattmeter across the entire circuit, including the current coil of the wattmeter and the ammeter, as indicated by the full lines in Fig. 11. This connection, it will be noted, makes the wattmeter read too much by the amount of the I^2R loss in the ammeter and in the current coil of the wattmeter; but as this loss is generally much less than the I^2R loss in the voltmeter and the potential coil of the wattmeter, connecting the potential terminals at C (Fig. 11) will give less error than if they were connected at B (Fig. 11).

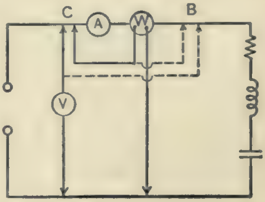


FIG. 11.

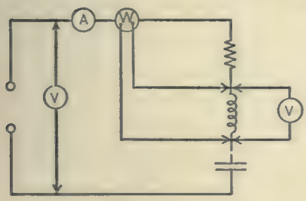


FIG. 12.

In measuring the power used in each part, and the drop across this part, it will be noticed that the potential coil of the wattmeter and the voltmeter are connected in parallel with the part of the circuit being tested. This is indicated in Fig. 12, where the coil is being measured. The current read on the ammeter, therefore, is not the current through the coil, but the vector sum of this current and the currents through the two meter circuits. The power indicated on the wattmeter is, moreover, the power used in the coil plus the power used in the two potential circuits. In general, a minimum error due to these effects will be made if an extra voltmeter is used, as indicated in Fig. 12, to hold the voltage impressed on the circuit constant as the individual parts of the circuit are being measured. With the voltmeter held at the value which obtained when the whole circuit was being measured, the ammeter is read before either potential circuit is connected across the part being measured. The wattmeter is then read with the voltmeter circuit open, and the voltmeter is then read with the potential circuit of the wattmeter open.

The current, voltage, and power for each part of the circuit being known, it is evident that a diagram similar to that of Fig. 7 can be constructed. The phase of the voltage across each part with respect to the current in that part is obtained by the ratio of watts to volt-amperes; this gives the position of the voltage drops with respect to the current, and the magnitude of the respective drops is read directly on the voltmeter.

By vector addition of the three drops, the impressed voltage is obtained in magnitude and phase; this can be checked because the impressed voltage was actually measured and its phase fixed by the ratio of circuit watts to circuit volt-amperes.

After having carried out these measurements at the low frequency, without changing L, R or C, increase the speed of the alternator used, to give just double the frequency, if possible; change the impressed voltage to bring the current back to exactly the same value it had for the previous run, and get circuit readings of volts, amperes, and watts, as well as for each part.

Now with the lowest frequency, arrange the three pieces of apparatus in parallel as in Fig. 9, putting an ammeter in series with each of the three branches. With a line voltage sufficient to bring the current in the inductive branch well up on the ammeter scale, read line current, voltage, and power, as well as each branch current. Now read the power in each branch by keeping the line voltage at the value just determined, and opening in turn each two of the three branches. If the power in the coil is desired, open the resistance and condensive branches; if the power in the resistance is desired, open the coil and condensive branches, etc. The connections are indicated in Fig. 13.

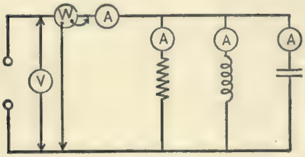


Fig. 13.

Now adjust the frequency of the alternator to just double its value for the above run, keeping the voltage the same as it was before. The current through the resistance should be the same as it was before, that in the condensive branch twice as much, and that in the coil about half as much. Take readings as for the lower frequency.

With an iron-core coil, get a series of readings between volts, amperes, and watts, holding current at some convenient fixed value, and varying the frequency through as wide a range as convenient; and also with frequency fixed at some value and current varied through as wide a range as convenient. Get about eight points for each run. Find the conductor resistance of the coil by continuous-current measurement (ammeter and voltmeter).

Measure the insulation resistance of the condenser by a continuous-current voltmeter of known resistance (the resistance of a voltmeter is generally given either on its scale, containing box, or some similar place). Take a reading on the meter when it is connected in series with the condenser across the 110-volt line, and another when the voltmeter is directly across the line. The resistance of the condenser is then (very nearly) equal to the resistance of the instrument multiplied by the ratio of the line voltage to the reading when the condenser was in series.

Curves.—For the two runs with the series circuit, construct voltage diagrams of the circuit similar to that of Fig. 7, and find on the diagram the line e.m.f. as the vector sum of the three drops; put in the same diagram the line e.m.f. as measured. For the two runs on the parallel circuit, construct current diagrams similar to that of Fig. 10, and find the line current as the vector sum of the three branch currents; on the same diagram plot the line current as measured.

For the two runs with the iron-core coil, plot values of resistance and coefficient of self-inductance, against current and against frequency, as the case may be.

Questions.—

1. What would be the power factor of the series circuit if the inductance reaction were just equal to the capacitance reaction?

2. Why does not the arithmetical sum of the drops across each part of the series circuit equal the impressed voltage?

3. Why does not the same idea then hold for the power used in each part and in the whole circuit?

4. The voltage across one part of a series circuit may be greater than the impressed voltage. Explain.

5. Why is the a.c. resistance of the iron-core coil so much greater than its c.c. resistance?

6. Why does its effective resistance decrease with increase of current?

7. Derive the equation used in finding the insulation resistance of the condenser.

8. A coil of 0.1 henry and a 5-ohm resistance are connected in series with a 50 m.f. condenser to a fixed-voltage, variable-frequency line. At what frequency will the current be a maximum? How much will the drop across the condenser be at this frequency, compared with the impressed voltage?

9. What would be the power factor of the above circuit at 60 cycles? Would the current lead or lag?

III. THE THREE-PHASE CIRCUIT

Object.—Study of current and voltage relations in various three-phase circuits. Power measurements in three-phase circuits, balanced and unbalanced.

Theory Involved.—The theory of voltage and current relations in three-phase circuits has been analyzed in Chapter IV, Volume II, and this material should be carefully studied before attempting to carry out the following experiment with three-phase circuits. Only a brief summary of the three-phase theory will be given here.

The three-phase alternator has an armature winding consisting of three similar groups of coils, spaced 120 electrical degrees apart; each of these groups is called a phase. The voltage of one group is called the phase voltage (e) of the machine, and the current in the coils of a group is called the phase current (i).

In case these phases are Y-connected, the safe current per terminal (there are three terminals) is the same as the safe current per phase, and the voltage between *any pair of terminals* is equal to the phase voltage multiplied by $\sqrt{3}$. In case the coils are improperly connected in trying to make this Y-connection, the three terminal voltages will not be equal. This has been called an unsymmetrical Y (see Section 40, Volume II), and is caused by connecting one of the phases in backward.

In case the coils are properly connected in delta (mesh) the voltage between terminals of the machine is the same as the voltage per phase but the safe current per terminal of the machine is equal to $\sqrt{3}$ times the safe current per phase. Whereas in making the Y-connection of the alternator, no damage will result even if one of the phases is improperly connected, in making the Δ-connection a large short-circuit current will flow if an incorrect connection is made. Before the last (third) connection of the Δ-connection is made, a voltmeter must be put across the open point, and the reading of the meter must be low before the last connection can be made. It will generally not be zero even with the proper connection; it may be as much as 25 to 50 per cent of the voltage of one phase, because of the presence of a third harmonic component in the voltage generated per phase, but this voltage will cause but little current to flow around the closed circuit when the last connection of the delta is made.

The load circuit connected to a three-phase line may be either Y- or Δ-connected, although the practice in lighting systems is always delta. In case the load is a three-phase motor of some kind it may be either Y- or Δ-connected; the operation would be just the same. In case the load is Y-connected, the current in each phase of the load will be the same as the current in the supply lines; for balanced load, the voltage across one phase will be $1/\sqrt{3}$ of the line voltage. In case the load is not balanced, the drop across the different phases of the load will be different, the difference depending upon the amount of unbalance. By a balanced three-phase load is meant one in which not only the impedances per phase are the same, but the power factor of each phase is the same; that is, not only must the impedances of the different phases be the same, but each phase must have the same resistance and reactance.

Thus, a three-phase load of

$$\begin{aligned} Z_1 &= 10, & R_1 &= 10, & X_1 &= 0, \\ Z_2 &= 10, & R_2 &= 8, & X_2 &= 6, \\ Z_3 &= 10, & R_3 &= 6, & X_3 &= 8, \end{aligned}$$

would have balance in so far as the magnitude of the different impedances is concerned, because each has a magnitude of 10 ohms. This would not be a balanced three-phase load, however, because the power factor of phase No. 1 is unity, of phase No. 2 is 0.8, and of phase No. 3 is 0.6.

In the case of a Δ-connected unbalanced load, the voltage impressed upon each phase will be the same, except for possible inequalities due to different IZ drops in the alternator windings and lines supplying power to the load. This unbalance in the voltage will not generally be large, possibly 5 per cent for badly unbalanced loads. In case the load is balanced, the current in each of the supply lines will be $\sqrt{3}$ times the current in one phase, but in case of unbalanced loads this relation will not hold good. As for the Y-connected load, the term " balanced load " implies the same power factor as well as the same impedance per phase. In case of bad unbalance it is possible for the current in one line to be zero, even though each phase is carrying a large current. It is also possible for the current in one line to be twice as great as the current in one phase, instead of only $\sqrt{3}$ times as much. In general, the line current will be the vector sum of the currents in the two phases to which the line is common, as shown in Section 102, Volume II.

In a balanced three phase load the total three-phase power is evidently three times the power used per phase; in any case it is the sum of the amounts of power used in the different phases. In the case of a

Y-connected load this three-phase power can evidently be measured by three wattmeters connected as shown in Fig. 14, each wattmeter registering the power in the phase to which it is attached. In a Y-connected load, however, the center of the Y is generally not available, as, for example, a Y-connected induction motor. The center of the Y-connected winding in such a case is entirely hidden in the end connections of the winding and so is not available for making connections. So the scheme of Fig. 14 is applicable only with a laboratory load.

In general, the power delivered by a three-phase line is measured by two wattmeters properly connected as shown in Fig. 15. The algebraic sum of the readings of the two wattmeters so connected always gives the total three-phase power, no matter how the load is connected, delta or Y, or whether it is balanced or unbalanced. The theory showing that the sum of the two readings does indicate the three-phase power is given in Sections 88 and 106, Volume II.

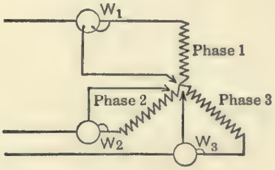


FIG. 14.

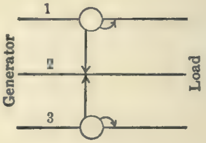


FIG. 15.

It may be that when properly connected (a test for proper connection is given later), one of the wattmeters reads backwards, so that the potential leads must be reversed to get a reading. This reading must then be called negative and so must be subtracted from the other wattmeter reading in calculating the three-phase power.

In testing for the proper connection of the potential leads of the wattmeters, they are connected as in Fig. 15, and then the correctness of the wattmeter in line No. 1 is checked by noting that it reads on the scale (that is positive), when line No. 3 is opened. If it does not, then its potential leads must be reversed so that it does. Then the wattmeter in line No. 3 is tested for proper connection, in the same manner; line No. 1 is opened and the potential coil of the wattmeter in line No. 3 is so connected as to make it read on the scale.

Now, when all three of the three-phase lines are closed it may be found that one of the wattmeters deflects backwards; such being the case, its potential leads must be reversed to make it read on the scale, but the reading so obtained must be called negative. Such a condition of affairs shows that the power factor of the load connected to the three-phase line is less than 0.5, that is, the angle of lag or lead is greater than 60 degrees.

With some types of load, it is not necessary to go through the procedure outlined above to find the proper connections for the wattmeter potential leads in order to tell whether or not one wattmeter reading is to be reckoned as negative. With such a load as a three-phase induction motor, we know that when the load on the motor is small the power factor is likely to be less than 0.5, and we know also that the power factor increases as the load on the motor increases, approaching 0.8 or 0.9 at full load. Hence, at light load we connect the wattmeters in such a way as to make both the meters read on the scale, and take readings, not knowing yet whether the smaller of the two readings is to be regarded as negative or not. When we increase the load on the motor, if the reading of the lower of the two wattmeters (the one having the smaller scale indication) decreases its reading, it is to be reckoned as negative. If it increases as load on the motor increases (thus increasing the power factor) the wattmeter reading is positive.

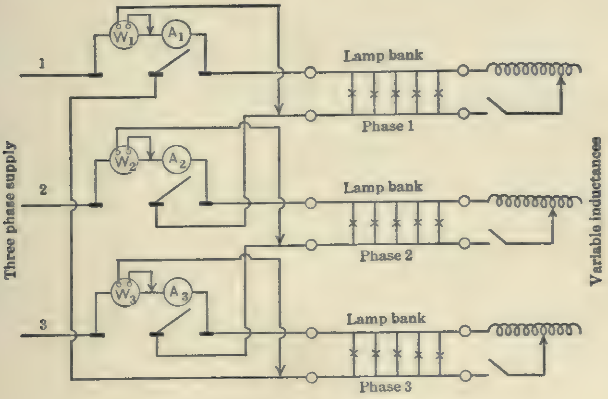


FIG. 16.

A convenient switching scheme for getting all necessary measurements for analyzing relations in a three-phase Δ-connected load is shown in Fig. 16. The three single-pole, double-throw switches are so inserted that the ammeters and wattmeters may readily be transferred from the lines to the phases. When adjusting or balancing the delta load (as may be called for in the test) the meters are connected in the phases by throwing the switches of Fig. 16 to the left; when it is desired to read the line values, the switches are thrown to the right.

For making a test on a Δ-connected, inductive load, the connection scheme of Fig. 16 is used, but in addition a variable inductance is put in parallel with each of the lamp banks. By suitable combination of lamps and inductance coil, practically any desired power factor can be obtained.

For making tests on a Y-connected load, the connections of Fig. 16 are slightly changed, as shown in Fig. 17, in which the Y-connection for an inductive load is shown. The variable-inductance coils are here shown in parallel with the lamp banks. By removing all three connections from the blades, and connecting them together, the delta-load arrangement is changed to a Y-load.

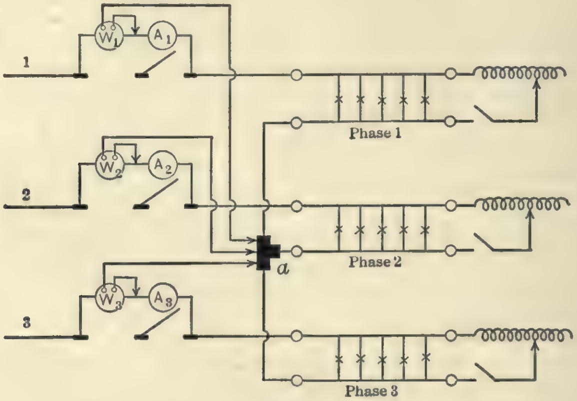


FIG. 17.

Procedure.—With the connections made as in Fig. 16, and with the meters connected in the phases, adjust the three phases so that the load is balanced (non-inductive), and read the phase currents. Connect the potential coil of W_1 across the phase No. 1 and read the power used in phase No. 1. Likewise get the power used in phases No. 2 and No. 3 by meters W_2 and W_3.

Now leaving the load fixed at this value, change the meters into the lines, by throwing the switches (of Fig. 16) to the right, and read the three ammeters. The three ammeter readings should be equal, and also equal to the readings in the phases multiplied by $\sqrt{3}$. Connect one end of the potential coil of wattmeter W_1 to line No. 1 (this may be done by connecting it to one of the current posts of W_1) and the other to line No. 2. Connect one end of the potential coil of W_3 to line No. 3 (on one of the current posts of W_3) and the other to line No. 2, and get a reading of W_1 and W_3. It is to be noticed that this connection of the two wattmeters is the same as that shown in Fig. 15. The sum of the readings of W_1 and W_3 should be equal to the sum of the three wattmeter readings when they were connected in the phases.

It is to be noted that W_1 and W_2 (of Fig. 16) could be used just as well for getting the three-phase power as W_1 and W_3. If W_1 and W_2 have their potential circuits connected to lines 1 and 3, and 2 and 3, respectively, the sum of their readings will be the same as was that of W_1 and W_3.

Carry out the above measurements for two values of current with balanced load and two conditions of unbalanced load. Then connect the variable inductances in parallel with the lamp banks. With the switches thrown to the left (meters in the phases), adjust the phases for equal currents and equal power factors. This is most easily done by cutting out the lamps (by switches, or by screwing them out of their sockets) and adjusting the three inductances to give equal currents in the three phases. Then add enough lamps in each phase to bring the power factor up to the desired value, putting the same number of lamps into each phase to keep the load balanced. Enough lamps are put in to make the ratio of watts to volt-amperes yield the desired power factor.

With balanced inductive load, take a set of phase readings and line readings, as was done for non-inductive load. Get one set of readings for a load of power factor about 0.8 and another about 0.4. In the latter case it will be found, when reading the power in the lines, that one of the wattmeters must have its potential leads reversed to make it read on the scale; its reading must then be called negative in getting the total power.

From the readings obtained in these runs check the formula for power factor of a three-phase load as determined by

$$\text{Cos}\,\phi = \frac{W_1 + W_2}{EI\sqrt{3}},$$

E and I being line voltage and current, respectively. The value so obtained should check with the value for which each phase of the load was adjusted.

Take another set of readings with the load unbalanced and again compare line and phase values; the two line wattmeters will again give the total three-phase power, but the formula for power factor (given in the preceding paragraph) will not check because the line current has not a definite value, having different values in each of the lines. Even if average line currents and voltages are used in the formula for power factor, the agreement between calculated and known average power factor will be approximate only.

Now, using the connection scheme shown in Fig. 17, find the relation between phase and line quantities for balanced non-inductive Y-load, as was done for the delta-load. In the Y-connection the phase and line current are evidently the same; it is the line and phase voltages which have the $\sqrt{3}$ relation. The sum of the two line wattmeter readings should check again with the sum of the three phase wattmeter readings. Take other readings for unbalanced, non-inductive loads, and then for inductive load, balanced and unbalanced. For balanced inductive load it will be found that the $\sqrt{3}$ relation for line and phase voltages holds good and the formula for power factor (from line quantities) agrees with the power factor as measured in the phases, but for unbalanced loads neither of these relations holds good.

For all conditions of load, however, the sum (algebraic) of the two line wattmeter readings is equal to the total three-phase power.

A convenient method for balancing the three-phase, Y-connected load consists in opening one line (say, line No. 3) and then adjusting phases Nos. 1 and 2 to equality by making the voltage drop across each phase the same. Then open line No. 1 and make the drop across phase No. 2 and phase No. 3 the same, *adjusting only phase No. 3* in getting the equality in voltage. In case of the inductive load, the three coils are first balanced, in the manner just described, there being no lamps connected in the circuits. After the coils have been balanced, enough lamps can be added (the same number in each phase) to bring the power factor of the load up to the desired value.

Construct vector diagrams of the current and voltages (to scale) for each of the three phase loads tested, and check, from the vector diagrams, the relation between line and phase values, as well as the readings of the line wattmeters. (For the vector construction showing how to get the readings of the line wattmeters, see Sections 88 et seq., Volume II.)

Questions.—

1. Briefly, why is three-phase power superior to single-phase power?

2. An alternator generates 110 volts per phase and can safely carry 50 amperes per phase. What will be its rating, in volts, amperes, and kv.-a., when Δ-connected and when Y-connected?

3. If we assume the efficiency of a three-phase induction motor as 92 per cent, and its power factor as 0.82, the line voltage being 440 volts, what is the current in each of the supply lines when it is delivering 75 h.p. of mechanical power? If the motor winding is Δ-connected, what is the current in each phase of the winding?

4. A three-wire power supply comes into the laboratory. Having a c.c. voltmeter and an a.c. voltmeter of suitable range, show what measurements you would make to find out whether it was three-wire continuous current, single-phase three-wire, two-phase three-wire, or three-phase.

5. If it is determined that the above supply is three-phase, what voltmeter measurement could you make to determine whether the alternator supplying the power is Y-connected or Δ-connected? Explain.

6. Three resistances of 10, 15, and 20 ohms are connected in Y to a 100-volt Y-connected alternator, and a neutral wire is connected between alternator and load. How much current does it carry? (See Section 100, Volume II.)

7. If no neutral wire is used in the above problem, what will be the voltage across each phase of the load, what will be the current in each wire, and what will be the voltage between the neutral of the load and the neutral of the alternator?

8. A 60,000-volt, three-phase, transmission line is delivering 5000 kw. of power to an induction motor load of power factor 0.80. What is the current in each wire of the line? If three single-phase transformers are connected to the transmission line, primaries in Y and secondaries in Δ, what will be the voltage of the line supplied from the secondaries, the ratio of each of the transformers being 190 to 1?

IV. THE ALTERNATOR

Object.—To obtain the important characteristics of the alternating-current generator by measurement. To obtain sufficient measurements to permit the prediction of its external characteristics for loads of different power factors.

Theory Involved.—The important characteristics of an alternating-current generator which are to be investigated in this test are the external characteristic curves with loads of various power factors, the synchronous impedance curve, and the standstill resistance and reactance of the armature. There are many other features of the alternator which have commercial importance, such as the efficiency, magnetization curve, and armature characteristics, but they cannot all be obtained in one laboratory period.

In ordinary commercial practice, the terminal voltage of an alternator would fall as its load is increased, unless some such device as the voltage regulator acted to prevent the drop. An armature has resistance and reactance, both of which use up some of the generated voltage; as these two drops, the IR drop and the IX drop, are proportional to the load current, I, it follows that the terminal voltage, if the generated voltage is held constant, will decrease more or less uniformly as the load increases.

The generated voltage of a given machine is fixed by the speed and field strength; it might therefore be thought that if the field current and speed were kept constant, the generated voltage would be constant. Such, however, is far from the fact with a modern generator; the load currents flowing through the armature will exert a powerful influence on the field strength, the effect being known as armature reaction. The actual field strength in the armature core can be thought of as due to two m.m.f.'s, that of the field coils and that of the armature coils, and as, in modern alternators the armature ampere-turns per pole (at full load) may be as much as 50 per cent of the field ampere-turns per pole, it is easy to see that even though the field current is held constant as the load is varied, the field strength will undoubtedly vary with the load current owing to the effect of the varying armature ampere-turns.

The exact effect of armature reaction of the field strength of the machine depends upon the power factor of the load being applied; for resistive load the effect is one which merely twists the main field around in the direction of rotation, the same action as occurs in a continuous-current generator when supplying load. For inductive loads, the armature reaction may be considered in two parts, one of which actually acts to demagnetize the field and the other to twist the field, the ratio of the two effects depending entirely upon the power factor. For a purely inductive load ($\cos \phi = 0$), no twisting action would occur, all of the armature ampere-turns being effective in demagnetizing the field. The opposite effect occurs for condensive load, the armature ampere-turns actually helping the field ampere-turns to magnetize the field. If the current does not lead 90 degrees (as ϕ of load is not equal to zero) there is a twisting action as well as the magnetizing action, the amount of twist decreasing, and the amount of magnetizing action increasing, as the power factor of the load approaches zero.

In a single-phase alternator the armature reaction is a pulsating effect, varying in magnitude and direction, whereas for the polyphase machine supplying a balanced polyphase load, the armature reaction is constant in magnitude and direction, as was shown in Sections 163 et seq., Volume II. For the single-phase alternator, the statement in the above paragraph, regarding twisting and demagnetizing action holds good for the average, or net, effect of the pulsating armature reaction.

That the change in terminal voltage of an alternating-current generator, as load is varied, is important, becomes evident if we consider the load to consist of incandescent lamps, for example. For an incandescent lamp, if the voltage decreases, the amount of light given off decreases very rapidly, while if the lamp is operated at higher than the rated voltage, a material shortening of the life occurs. A decrease of 6 per cent from rated voltage cuts down the amount of light by 20 per cent; an increase of 6 per cent above rated voltage reduces the normal life by 55 per cent. (See curves in Pender's "Handbook for Electrical Engineers," p. 917.)

The question of variation in terminal voltage of an alternator is then an important one. That alternator giving the most nearly constant terminal voltage, with varying load, will most satisfactorily carry a lighting load (voltage regulators not being considered).

If its rated load is put on an alternator and the field current then adjusted to give rated terminal voltage, and then, while field current and speed are maintained constant, the load is taken off, the terminal voltage will change, and the amount of the change is a measure of the regulation of the alternator. In case of average commercial load (lagging power factor), the voltage will rise as load is taken off, and the regulation is positive; whereas if a capacitive load of low power factor is used, the voltage will actually fall as load is taken off, and the regulation is negative. Quantitatively, the regulation is given by

$$\text{Per cent regulation} = \frac{\text{No-load voltage} - \text{full-load voltage}}{\text{Full-load voltage}} \times 100.$$

The ordinary alternator will give a regulation, with reactive load, of between 5 and 20 per cent, depending upon the constants of its armature (resistance, reactance, etc.).

The synchronous impedance of the alternator is a fictitious quantity which serves as a measure of the effect of the armature winding in changing the terminal voltage as load is varied. It lumps together the armature resistance drop, the reactance drop, and the effect of armature reaction. By the use of the synchronous impedance, the action of the alternator with increasing load can be reasonably well predicted without considering as two separate effects the armature reactance drop and the armature reaction. The value of the synchronous impedance can best be obtained by considering how it is measured. With the armature short-circuited through suitable ammeters, sufficient field current is passed through the field windings to force full rated current to flow in the short-circuited armature, when it is rotating at rated, or synchronous, speed. The short-circuit is then removed, speed and field current held constant, and the voltage generated in the armature is measured. This voltage divided by the full-load current (for a single-phase machine) gives the synchronous impedance of the armature. As explained in Chapter V, Volume II, in case the machine is three-phase, it is always considered as a Y-connected winding and the characteristics of the winding determined per phase. Thus the synchronous impedance per phase is determined by getting the voltage per phase (line voltage $\div \sqrt{3}$), and dividing this by the line current (which is also the phase current for a Y-connected winding).

Then, with the armature stationary, the resistance per phase is generally determined by continuous current; this resistance is obtained for one phase by passing continuous current between two terminals of the machine, reading volts and amperes, thus getting resistance between terminals, and dividing the resistance by two. Or if effective resistance per phase is to be obtained, the armature (with machine stationary) is treated as a three-phase load. Full-load current is forced to flow in it, the three-phase power is measured by the two-wattmeter method (see Section 92, Volume II); this power is divided by three to get the power per phase, and this amount of power is divided by the square of the current. This effective resistance per phase will always be considerably greater than the value of resistance per phase determined by continuous-current test, sometimes as much as three times the continuous-current value.

In predicting the external characteristic of the alternator (to compare with the measured external characteristic, as a test of the validity of the prediction scheme) the problem is worked graphically, in terms of the voltage per phase. *No matter how the machine is actually connected, it is treated as a Y-connected winding, and the results obtained are just as correct whether the machine is actually Δ-connected or Y-connected.*

A machine is always rated to give a certain terminal voltage when carrying rated full-load current. This rated terminal voltage is first changed to rated terminal voltage " per Y phase " by dividing the actual rated voltage by $\sqrt{3}$.

In Fig. 18 is shown the construction for predicting the external characteristic in terms of phase voltage for a load of unity power factor. The load current is used as reference vector and is shown at OI. The full-load resistance drop, per phase, is laid off in phase with the current at OA. With the full-load synchronous impedance drop per phase as a radius, an arc is struck with O as center, this arc intersecting the perpendicular erected at A in the point B. Then OB is the full-load synchronous impedance drop per phase, in its proper phase relation with respect to the load current OI. The synchronous reactance drop per phase is obtained, if desired, by projecting OB on the perpendicular through point O; it is shown as OC.

In phase with the load current OI is laid off, to the same volt scale as has been used for OA and OB, the rated terminal voltage of the machine $\div \sqrt{3}$; this is shown at OD. Under rated full-load conditions, then, the machine gives a terminal voltage per phase of OD and has an internal impedance drop per phase of OB; the generated voltage per phase must therefore be the vector sum of these two, shown at OE. When using the synchronous impedance method of determining the external characteristics, the generated voltage, OE, is regarded as constant no matter what the load may be. Actually, due to armature reaction, it does not stay constant, but by using the " synchronous impedance " instead of the actual impedance of the armature, the effect of armature reaction is indirectly cared for in the construction of Fig 18.

As the load on the alternator decreases, the impedance drop in the armature winding must decrease, it being proportional to the current;

the generated voltage, *OE*, must stay constant, and hence its locus is the arc *EHF* of Fig. 18. At half load the impedance drop per phase is one-half of *OB*, shown at *OG*. This voltage *OG*, combined with the terminal voltage at half load (as yet unknown), must give the generated voltage, equal in magnitude to *OE*. By constructing the line *GH* parallel to *OI*, and the line *HJ* parallel to *GO*, the terminal voltage at half load is found to be *OJ*. It is seen that the construction does make the vector sum of the terminal voltage, *OJ*, and the internal impedance drop at half load, *OG*, equal to the constant generated voltage, *OH* (*OH* is equal in magnitude to *OE*).

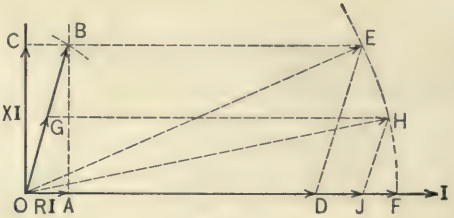


Fig. 18.

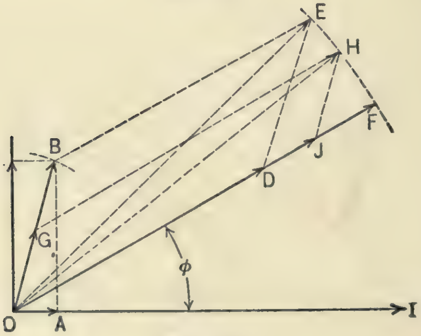


Fig. 19.

To get the terminal voltage for any load whatsoever a proper proportion of the full-load impedance drop, *OB*, is taken; from the end of this impedance vector, a line parallel to *OI* is taken across to intersect the arc *EHF*, and from this intersection a line is drawn, parallel to *BO*, to intersect *OI*, and this intersection gives the terminal voltage.

In case the load is inductive, a construction quite similar to that of Fig. 18 is used; it is shown in Fig. 19. Using the load current as reference vector again, the phase of the terminal voltage is laid off ahead of the current vector by the angle ϕ, cos ϕ being the assumed power factor of the load. The rated terminal voltage (per phase) is laid off at OD, the synchronous impedance is laid off as it was before, and the generated voltage found by adding vectorially OB and OD; it is shown at OE. An arc with OE as radius is struck, and by construction exactly similar to that of Fig. 18, the terminal voltage for any other load is found. In Fig. 19 it is shown for half load at OJ, and for no load at OF.

The terminal voltages obtained from these diagrams must be multiplied by $\sqrt{3}$ to get the terminal voltages of the machine.

In case a condensive load was assumed, the terminal voltage per phase would be laid off behind OI by the proper angle, and the generated voltage found by a construction exactly similar to that of Figs. 18 and 19. In case the angle of lead is assumed sufficiently large, it will be found that the terminal voltage actually decreases as the load decreases, whereas for the two other cases it increased. The regulation of the machine with condensive load may be zero, or even negative, therefore.

Procedure.—The first part of this experiment consists in actually loading the generator and, by taking readings of terminal voltage and load current, getting enough points to actually construct the curve, showing the relation between load current and terminal voltage, which is called the external characteristic. For non-inductive loads, water-barrels or lamp-boards may be used, preferably connected in delta, if a three-phase machine is being tested.

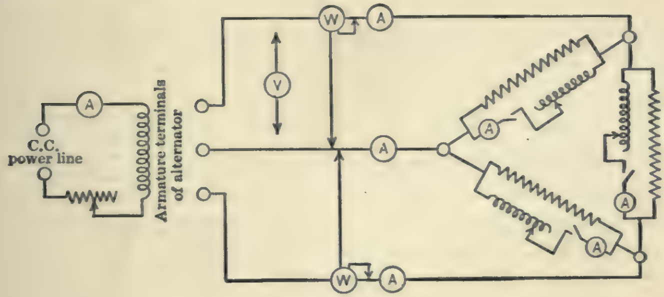


FIG. 20.

After the alternator is running at rated speed, adjust the load current and field current, so that rated terminal voltage is obtained with rated current. The easiest manipulation is permitted if six ammeters are used with the three-phase load, about as indicated in Fig. 20. The variable inductances are connected in parallel with the Δ-connected lamp bank, with single-pole switches so that they can be cut out until the run with the inductive load is being carried out.

With the inductance switches open, the number of lamps put in each of the banks is increased uniformly (the terminal voltage being kept at rated value by the field rheostat, and the speed kept constant by manipulation of the prime mover) until rated current is flowing in each line at rated voltage and speed. The field current is noted and kept constant at this value for the rest of the run. Vary the number of lamps in the load in equal steps, reading terminal volts (on each of the three pairs of lines), load current in each of the three lines, and power on the two wattmeters. About four points should be obtained between zero load and 25 per cent overload, as well as these two extreme points, making six points in all. (Much time may be spent in trying to balance a three-phase load exactly; if the line ammeters agree within 5 per cent, the adjustment is good enough for ordinary work.) For this run, the sum of the two wattmeter readings should be equal to $EI\sqrt{3}$, E and I being line values.

For the inductive-load run, somewhat more manipulation is required, as the right amount of current must be obtained in each branch of each phase of the delta load. Let us suppose that the machine is rated at 110 volts, 50 amperes, and we are to get the external characteristic for inductive load of $\cos \phi = 0.8$. The 50 amperes must be made up of $50 \cos \phi = 40$ amperes active current, and $50 \sin \phi = 30$ amperes reactive current. The reactive current must be taken by the inductances and most of the active current by the lamp banks. (The inductances take a small amount of active current.)

Now, a line current of 50 amperes requires a current of $50 \div \sqrt{3}$, or 28.8 amperes in each phase of the delta load. Of this current, $28.8 \times \sin \phi = \frac{50}{\sqrt{3}} \times \sin \phi = 50 \times 0.346 = 17.4$ amperes must be reactive and 23.2 amperes active.

To get the full-load rated conditions, therefore, the speed and terminal voltage are held constant at rated value and the inductances are adjusted until each of them is drawing a current of 17.4 amperes, as shown by the ammeter directly in series with the coils. The lamp banks are then increased in equal steps for the three phases, until each of the line ammeters reads 50 amperes. The readings of the two wattmeters, W_1 and W_2, should then be taken, and the ratio of their sum to the product $EI\sqrt{3}$ should give the desired power factor of 0.8. It generally will not be quite 0.8; but if it varies 2 per cent either above or below the specified value, the setting may be regarded as satisfactory.

Read the line volts (between each pair of lines), line amperes (in each line), and power (on the two wattmeters), as well as field current and speed. Keeping the field current at this value, and speed at rated value, get a series of points as was done for resistive load. At half load, for example, the current through each inductance should first be adjusted to 8.7 amperes, and the lamp-bank then adjusted to give 25 amperes in each line. As the lamp-bank is changed, the line voltage will change somewhat, so that a resulting change in the current through the coils will occur. Thus, at least two successive adjustments will be necessary to get the desired conditions, namely, 8.7 amperes in each coil and 25 amperes in each line.

In getting the synchronous impedance, the field is first excited by potentiometer connection to the supply line; a low value of field current will be required in this test. Make connections as in Fig. 21, the ammeters being of suitable range to carry full-load current. When the field current has been reduced to zero the armature is short-circuited as shown; short leads of about the same length should be used in each line. Long leads will add appreciably to the resistance of the armature circuit, and if they are of uneven lengths the three ammeters will not read alike, as they should. The field current is now slowly raised until full-load current is flowing in each of the three lines, the speed of the alternator being at rated value. While field current and speed are kept at these values, the short-circuit switch is opened so that no current can flow, and the voltage of the armature is measured between each pair of wires. The average of these line voltages (they should all be the same) divided by $\sqrt{3}$ gives the full-load synchronous impedance voltage per phase, to be used in constructing Figs. 18 and 19.

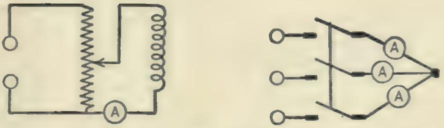
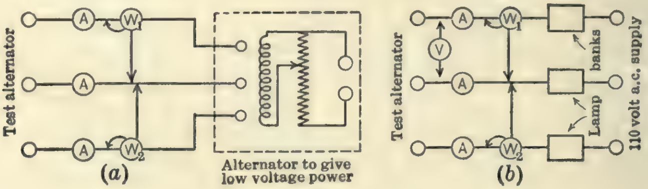


FIG. 21.

Now, using a source of low-voltage power, treat the armature as a three-phase load and measure its effective resistance and impedance. In case a low-voltage alternator is available, the connection is made as in Fig. 22*a*; but if such a machine is not available, the laboratory three-phase power supply may be used by putting a lamp-bank in each line. Adjust the power supply (by field excitation in Fig. 22*a*, and by the number of lamps in each bank in Fig. 22*b*) to get full-load current in the machine being tested, and read voltage, current and power. It may well be that the reading of one of the wattmeters should be called negative in this test, the power factor being less than 0.5. To test for this condition, carry out the procedure given in Section 98, Volume II.

The effective resistance per phase is obtained by taking the quotient of $\frac{1}{3}$ the power input to the armature, by the square of the average line current. The standstill impedance drop of the armature per phase (a quantity not used in this test) can be obtained by dividing the line voltage by $\sqrt{3}$. This full-load standstill impedance drop will be found to be much smaller than the synchronous impedance drop per phase.

In making the above test it is best to short-circuit the field winding. This will act like the secondary of a step-up transformer and will have a high voltage generated in it, being dangerous to those making the test, as well as to the insulation of the field winding. On a small 60-cycle machine (say, 10 kv.a.) the induced voltage may be as high as 2000 volts.



(*a*) (*b*)

FIG. 22.

In case it is not desired to use the effective resistance of the alternator in predicting its characteristics, the continuous-current resistance may be used; it will make practically no difference in the accuracy of the result. To measure the c.c. resistance per phase, pass a continuous current (equal to full-load rated current) through any circuit of the stationary armature, by using any two of the terminals. Reading amperes and volts, the continuous-current resistance of two phases in series will be obtained and the resistance per phase is taken as $\frac{1}{2}$ of this value. Even though the machine is actually connected in delta, the resistance per Y-phase so obtained is the proper one to use in predicting the external characteristics by the construction and methods of Figs. 18 and 19.

Curves.—With load current as abscissa, draw in full line the external characteristics of the generator as obtained by actual measurements in the two load runs, indicating clearly all measured values on the curve sheet. By suitably distinguishable points, show the corresponding values of terminal voltage obtained by the prediction method as carried out in Figs. 18 and 19.

Questions.—

1. With low field excitation, the armature of an alternator is short-circuited through an ammeter, and with constant field current the speed is varied through a wide range. The current through the short-circuited armature remains practically constant. Explain.

2. Why does the current through the variable inductances used increase as the air gap is lengthened?

3. Why is the standstill impedance of an alternator armature less than its synchronous impedance?

4. Briefly, how does the voltage regulator hold the terminal voltage of an alternator constant as load varies? (See Section 191, Volume II.)

5. A Y-connected alternator has per phase $X = 2.5$, $R = 0.5$ and voltage between lines (with no current flowing) of 6600. About how much would the armature current be if the alternator were short-circuited? Explain.

6. If the resistance of a three-phase alternator is 0.1 ohm and reactance 0.6 ohm, per Y-phase, and the terminal voltage of the machine is 110 volts when 25 amperes is being supplied to a resistive load, what will be the no-load terminal voltage?

7. When stationary, a certain three-phase machine had its armature connected to a 60-cycle supply line and the readings taken were 18 volts (average of three line readings), 50 amperes (average of three readings), 625 watts, and 100 watts. What was the impedance, reactance, resistance, and self-induction of the winding per Y-phase? (Two answers possible.)

V. THE CONSTANT-POTENTIAL TRANSFORMER

Object.—To study the single-phase, constant-potential transformer, its efficiency, power factor, and regulation by loading. Determination of losses and prediction of efficiency. Variation of exciting current with variation of impressed voltage.

Theory Involved.—There are many three-phase transformers in use to-day, in power houses and substations, but by far the vast majority of constant-potential transformers are single-phase. All the transformers used in the distribution circuits of a lighting network, for example, are single-phase. This test on transformers will therefore deal with single-phase operation only.

As pointed out in Chapter VII, Volume II, the two fundamental underlying ideas in the theory of transformer operation are the essential constancy of the flux density in the laminated core, as load is varied, and the essential equality of the volt-ampere product of the secondary circuit to the volt-ampere product of the primary. The flux density in the core does change slightly with the load because of the effect of the IR drop in the primary winding, an effect which, with the ordinary commercial transformer, permits a decrease in flux density of possibly 1 per cent, from no load to full load. The equality of secondary and primary volt-amperes holds good to within less than 1 per cent at full load (resistive) but at very light loads the equality is not satisfied. At quarter load, for example, the primary volt-amperes may be 10 per cent or more in excess of the secondary volt-amperes, and at no load the secondary volt-amperes are of course zero, whereas, owing to the exciting current, the primary volt-amperes may be 5 to 10 per cent of full-load rated volt-amperes.

In a small generator or motor (say, 10-kv.-a.) the maximum efficiency might be 90 per cent; the 10 per cent losses would be made up of I^2R losses in armature, friction and windage losses, and core losses. In the corresponding transformer there are no mechanical losses, as there are no moving parts. Moreover, the I^2R and core losses can be made much smaller than in the moving machine of corresponding size, owing to the more compact electric and magnetic circuits. The result is that, whereas the rotating machine has an efficiency of 90 per cent, the corresponding transformer has an efficiency of about 95 per cent.

Because it is so high, the efficiency apparently cannot be measured with much accuracy if the ordinary output-input method is used. Thus, if the true efficiency is 96 per cent and the meters in the input circuit read 1 per cent low, and those in the output circuit read 1 per cent high, the efficiency from test will be 98 per cent. This seems like a large error, but actually it is an error of only about 2 per cent, in so far as efficiency is concerned. If it is the losses of the transformer that we are interested in, it is evident that the above method of getting them (output-input) is extremely inaccurate; in the case given the losses would be found experimentally to be only one-half as much as their true value.

This inaccuracy in measured efficiency, due to poor calibration of meters, can be eliminated if the same meters are used for measuring both input and output; in this way the efficiency by the input-output method can be obtained to better than 1 per cent. A convenient switching scheme for using the same meters in primary and secondary is shown in Fig. 23. The current coil of the wattmeter and the ammeter can be thrown into the primary circuit by closing S_3 to the left and opening S_1. If S_2 is closed, load may be put on the secondary circuit. The potential coil of the wattmeter and the voltmeter V_2 are connected across the input terminals of the transformer by closing switch S_4 to the left. By closing S_1, throwing S_3 and S_4 to the right, and then opening S_2, the meters are properly introduced into the secondary circuit. The voltmeter V_1 is left permanently on the primary terminals to make sure that the impressed voltage is at its proper value whenever readings are taken in the secondary circuit; obviously its reading is not to be used in calculating the input to the transformer.

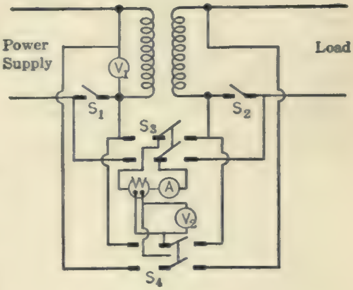


FIG. 23.

The power factor of the secondary circuit must, of course, be unity, if resistances such as lamps or water rheostats are used. However, it may well be found that the product of volt-amperes in the load circuit does not check exactly with the wattmeter reading of the load. If the voltmeter, for example, reads 1 per cent low and likewise the ammeter, and the wattmeter reads correctly, the measured power factor of the load circuit will be 102 per cent, evidently an impossible figure. To get rid of this source of possible error, the voltmeter and ammeter may be called correct, and the wattmeter may be calibrated in terms of these two instruments; that is, knowing the load power factor to be unity, we make the three instruments show it to be so. Any two of them might be called correct, and the third calibrated in terms of them, so that the operation suggested above is as good as any.

Hence, when determining the efficiency and regulation of the transformer, the readings of the secondary circuit serve also to give a calibration curve of the wattmeter; a curve is plotted with wattmeter readings as ordinates and volt-amperes as abscissa. The departure of the curve from a 45-degree line gives the correction to make in the wattmeter reading in calculating power factor for any of the other sets of readings obtained. A typical set of results might be, with the instruments connected in the secondary load circuit, volts 108, amperes 50, watts 5550. This set of readings would indicate that at this part of the wattmeter scale 150 watts should be subtracted from the reading to make it agree with the voltmeter and ammeter readings. A corresponding set of readings in the primary circuit, with the same load on the secondary circuit, might be, volts 220, amperes 26, watts 5730. As this reading on the wattmeter is practically at the same part on the scale as 5550, where a minus correction of 150 watts is to be applied, we must call the primary watt meter reading $5730 - 150$, or 5580 watts. The efficiency is then $5400 \div 5580 = 96.6$ per cent, the secondary power factor is $\frac{5400}{108 \times 50} = 100$ per cent, and the primary power factor is $\frac{5580}{220 \times 26} = 97.8$ per cent. Other points on the curves are similarly obtained, and the results obtained should be accurate to better than 1 per cent if care is used in taking the readings.

The regulation of a transformer is defined as the ratio of (no-load secondary voltage − full-load secondary voltage) to full-load secondary voltage, the primary impressed voltage being held at that value which gives the rated secondary voltage at full load. With a good transformer it will not be more than 2 or 3 per cent.

As the losses in a transformer are very definite in character, it is easy to set up conditions such that the transformer, without being loaded at all, is subjected to the same losses as it would be were it loaded. The losses of a transformer may then be measured without supplying more than just enough power to supply these losses. Having measured these losses for various values of current, it is very simple to predict the efficiency from the relation

$$\text{Efficiency} = \frac{\text{Output}}{\text{Output} + \text{Losses}}.$$

Any output at which the efficiency is desired *is assumed*, and, from the previously ascertained loss curves, the losses which would occur if the transformer were actually delivering this output are obtained. Then, by the use of the above formula, the efficiency is calculated.

The losses in a transformer can readily be measured to 1 per cent, and as they are only 10 per cent of the output at full load, the efficiency determined by the above formula is much more accurate than can be obtained by the output-input method. This loss method is the one ordinarily used in commercially determining the efficiency of a transformer. It is to be noted that if for some reason the losses cannot be obtained with an accuracy better than 10 per cent, even then the efficiency determined by the loss method is bound to be better than 1 per cent. Besides the advantage of the better precision obtained by the loss method, it is always preferred to the input-output method because in using the loss method it is not necessary to provide facilities for loading (not easy with a large transformer), and because of the energy loss required in the input-output method.

The core loss is measured by impressing on the primary a voltage equal to that required to give the secondary terminal voltage, at full load, that value at which the transformer is rated. Having the value of voltage impressed and the frequency at the rated values, the input is read by a suitable wattmeter; the reading is the core loss, assumed to be constant for all values of load. Actually there is a small I^2R loss also incurred in the test, but it is negligible, as will now be shown. The current required in the primary coil when the secondary is carrying no current (called the exciting current) is never more than 10 per cent of full-load rated current and generally about 5 per cent of this value. The secondary coil is carrying no current when the core loss is measured. The I^2R loss involved therefore (10 per cent exciting current assumed) is only $\frac{1}{2}$ per cent of the full-load I^2R loss of the transformer; as this full-load I^2R is about equal to the iron loss, the wattmeter reading when determining the iron loss is slightly high, but even with 10 per cent exciting current only $\frac{1}{2}$ per cent high. With 5 per cent exciting current it is only $\frac{1}{8}$ per cent high. Thus the wattmeter reading, with secondary not loaded, may be assumed as all core loss with negligible error.

The copper loss (I^2R loss) is measured by short-circuiting the secondary winding (or whichever is the low-tension winding) and impressing on the primary just sufficient voltage, at the rated frequency, to force full-load rated current through the short-circuited secondary. When full-load current is flowing in the secondary, full-load current will also be flowing through the primary, according to the fundamental principle of the transformer. Hence the I^2R loss in each coil of the transformer is the same as it would be if the transformer were delivering rated current to some real load, such as lamps or motors. If there is a suitable wattmeter in the primary (the one to which the power supply is connected) its reading will give the full-load I^2R loss in both windings of the transformer. Although the wattmeter is connected in the primary circuit only, it is evident that whatever power is used up in the secondary as I^2R loss must be coming from the primary circuit, and so be registered on the primary wattmeter.

Just as there is a slight I^2R loss occurring in the transformer when making the iron loss test, so there is a small core loss when making the copper loss test. With the average transformer, the voltage required in the primary to force full-load current through the secondary is about 5 per cent of the rated voltage. As the core loss varies with the impressed voltage at a power between the 1.6th and the 2nd, it follows that the iron loss when making the copper loss test will be about (5 per cent)^2 of the normal iron loss; this is, evidently a negligible error.

It follows then that by measuring the input, secondary open-circuited, normal voltage and frequency on primary, the iron loss is obtained; by reading the input with secondary short-circuited, and carrying full-load current, the full-load copper loss is obtained. As the core loss is independent of load, and the copper loss varies with the square of the load current, the total losses in the transformer for any assumed load can easily be computed.

The power factor of the primary can be calculated (or obtained from a vector diagram) for any assumed magnitude and power factor of secondary load, if the magnitude and phase of the exciting current are known; this is obtained when making the core loss test. The reactive volt-amperes required by the assumed secondary load are calculated; this number of reactive volt-amperes will be required in the primary. When the voltage ratio of the transformer is known, therefore, the primary reactive current required to supply a certain secondary reactive current is found to be equal to this secondary reactive current multiplied by the voltage ratio of the transformer. The primary reactive current so obtained is added to the magnetizing current (algebraically) and thus the total primary reactive current is obtained. The active component of the assumed secondary load is divided by the previously calculated efficiency of the transformer at this load and multiplied by the ratio of the transformer, to give the primary active current. The two components of primary current being known, the power factor can at once be calculated.

From the copper loss test the impedance drop in the transformer can be obtained by measuring voltage and primary current, and from this, if desired, the regulation of the transformer for any assumed load may be obtained in the same manner as was used for the alternator (Exp. IV).

Procedure.—It is convenient in the laboratory to use in this test a transformer having a ratio of unity or thereabouts, as the same meters may then be used in both primary and secondary circuits. Wire up the apparatus as shown in Fig. 23, using an ammeter and wattmeter of sufficient capacity to carry 50 per cent overload on the transformer. In case the transformer is one of commercial ratio (say, 20 to 1) it will be necessary to use current and potential transformers if the same meters are to be used in the two circuits, as shown in Fig. 24. In the high-tension side, a 20 : 1 potential transformer, *A*, reduces the voltage to 110 volts for the 110-volt voltmeters and the 150-volt potential coil of the wattmeter. In the low-voltage side, the current transformer, *B*, reduces the secondary current to such a value that the same ammeter and current coil of the wattmeter are suitable for use in both high- and low-tension windings.

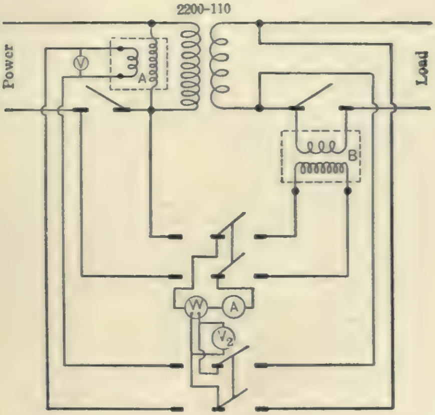


FIG. 24.

Do not handle the meter connections while the 2200-volt line is alive.

Put a non-inductive load on the secondary and increase this until full-load rated current is flowing. While this load adjustment is being carried out, the voltage impressed on the primary must be so changed that when full-load current is flowing in the secondary, the secondary terminal voltage is at its rated value. Read V_1 and during the load run now to be carried out, the reading of this meter is to be maintained constant at the value just determined. Take readings of input and output (volts, amperes, and watts) for $\frac{1}{8}$, $\frac{1}{4}$, $\frac{1}{2}$, $\frac{3}{4}$, rated, and $\frac{5}{4}$ rated secondary load.

Measure the iron loss and exciting current by getting accurately the input to the primary for no load on the secondary, the voltage impressed on the primary being the value used throughout the load run, and the frequency being at its rated value. It is likely that a wattmeter and an ammeter, other than those used in the load run, should be used for this iron-loss determination. The ammeter and the current coil of the wattmeter used for the iron-loss test should have a capacity about 10 per cent of the rated full-load current of the transformer. It is advisable to put a short-circuiting switch around these meters, to be closed while the transformer is being switched to the line.

While these meters are connected in the circuit, carry out a test to see how the exciting current and iron losses vary with impressed voltage, frequency being maintained at its rated value. Take points from about 50 per cent of rated voltage to such a voltage (higher than rated) that the exciting current increases to about five times its normal value; a sufficient number of points should be obtained to draw an accurate curve showing how the exciting current varies with voltage.

If time permits make another run, maintaining rated voltage and varying the frequency through as wide a range as feasible.

Measure the copper loss by connecting the transformer as shown in Fig. 25; the secondary (low-tension coil) is short-circuited through an ammeter with a range somewhat in excess of the rated full-load current; the wattmeter used in the primary should have a current rating equal to full-load primary current. The alternator supplying the power for the test should have its field excited by potentiometer connection, as it will be necessary to impress a very low voltage on the primary to force full-load current through the short-circuited secondary. As wattmeters are not generally available which have a potential circuit designed for lower than 75 or 150 volts, it is evident that because of the very low voltage impressed on the primary (about 5 per cent of rated voltage) the wattmeter will give a very low reading, which cannot be read with any reasonable precision. To obviate this difficulty, a potential transformer is used in the primary circuit, so connected as to step up the primary voltage ten or twenty times, to give a reasonable reading on the wattmeter and voltmeter. This will not be neces-

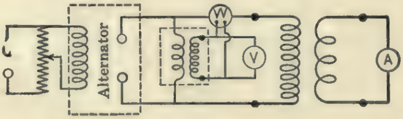


Fig. 25.

sary if the primary side of the transformer is designed for 2200 volts, as ordinary wattmeters and voltmeters will be just about right for such a transformer.

Ordinarily, the potential transformers used for instruments are of the step-down kind, designed to lower the voltage to be impressed on the meters. Such transformers will not have quite the same ratio when used for raising a voltage as when used for lowering a voltage; but if no step-up potential transformer is available, a step-down one may be used without introducing a very large error.

The true ratio of the transformer thus used may be obtained by placing a low-reading voltmeter directly across the primary of the power transformer.

With the connections as in Fig. 25, read voltmeter, wattmeter, and ammeter for such values of impressed voltage as give a secondary current as high as about 25 per cent overload, getting about six points for a curve. Have the frequency at its rated value during this test.

By continuous current, measure the conductor resistance of both primary and secondary windings.

Curves.—Using secondary load current as abscissa, plot efficiency, power factor, and secondary terminal voltage, as determined from the load run. On another sheet, plot core loss and copper loss against secondary current. Two curves of copper loss are to be plotted, one obtained from the short-circuit test and one from the values calculated from the resistances of the coils measured by continuous current. On this sheet, plot also the total loss curve (using copper loss determined by short-circuit run). From the curves, calculate the efficiency of the transformer for several values of load current and plot the values so obtained on the first curve sheet for comparison with the measured efficiency.

On another curve sheet, show how the exciting current and iron loss vary with impressed voltage, using voltage as abscissa.

Questions.—

1. A ten-to-one transformer has a primary resistance of 12.6 ohms and a secondary resistance of 0.117 ohm. What is the effective resistance of the transformer in terms of primary current?

2. A transformer has a primary rating of 6600 volts and 150 amperes. The exciting current is 7 per cent of full-load current and the iron loss is 16.5 kw. What is the no-load power factor? What are the active and reactive components of the exciting current? What is the effective resistance?

3. If the I^2R loss of the above transformer is 5.75 kw. at half load, what is the full-load efficiency?

4. A transformer has a rating of 220 volts and 75 amperes. Its full-load

efficiency is 96.7 per cent and the input at no load, under normal voltage and frequency, is 235 watts. What is the copper loss at quarter load?

5. A 15-kv.a. transformer supplies full rated load to a lamp load for 2 hours a day, half rated load for 2 hours, and quarter load for 3 hours a day. Its full-load copper loss is 3 per cent of its rating and its iron loss is $1\frac{1}{2}$ per cent of its rating. What is its all-day efficiency? At what load is the efficiency a maximum?

6. Why should a potential transformer give incorrect ratio if it is used as a step-up transformer, instead of as a step-down, as it was designed?

7. A potential transformer designed to operate one voltmeter is used for supplying the power to operate a voltmeter, potential circuit of a wattmeter, frequency meter, and the potential circuit of a power-factor indicator. What errors will be introduced in the readings of these meters, and why?

VI. THE INDUCTION MOTOR

Object.—To study the operating and starting characteristics of the induction motor; reversal of rotation; effect of rotor resistance on starting torque, efficiency, power factor, etc. Determination of pull-out torque.

Theory Involved.—As described in detail in Chapter VIII, Volume II, dealing with the induction motor, the stator, or stationary part, is connected electrically to the power supply, whereas the rotor, the rotating part, has no electrical connection to the power supply at all. Practically all induction motors are wound for polyphase power supply because of the much better starting characteristics of the polyphase compared to the single-phase motor. Whereas the single-phase induction motor, as such, has no starting torque at all, the polyphase motor has a reasonably good starting torque, which can be augmented if necessary by an easily accomplished change in the rotor circuit resistance.

A polyphase winding, supplied with polyphase currents, produces a rotating magnetic field. This magnetic field, if it could be stopped for inspection at any instant, would be seen to be sinusoidal in its space distribution. There being no salient poles on the stator or rotor, this sinusoidally distributed magnetic field remains of the same strength as it rotates; that is, the maximum strength of magnetic field, which will of course be at different parts of the stator at different moments, will always be of the same magnitude.

In Fig. 26 is shown the magnetic field distribution of a four-pole motor; it has maximum field density at four points around the air gap, A, B, C, and D, and these positions of maximum density are the poles of the motor, is so far as it has any. One pole is centered in the line X–Y, where the flux has its maximum density, $B_{\max}$; the sinusoidal distribution of flux is determined by the fact that at any other position, distant θ electrical degrees from X–Y, the flux density is $B_{\max} \sin \theta$.

As this magnetic field rotates at a uniform velocity, it follows that at any fixed point in space, the flux density goes through sinusoidal variations with respect to time, that is, $B = B_{\max} \sin 2\pi ft$, where f is equal to one-half the number of poles (points of density $B_{\max}$) passing the point in question each second.

The magnetic field utilizes the rotor for part of its path; any conductor on the periphery of the rotor will therefore have a sine wave of voltage induced in it, the frequency of this e.m.f. being the same as the frequency of the power supply if the rotor is stationary. In case the rotor is turning in the same direction as the field, a conductor is cut by the revolving magnetic poles less frequently; therefore the frequency of the rotor e.m.f. diminishes as the rotor speeds up, being zero if the rotor should happen to be turning at the same speed as the field, a condition which never occurs in motor operation. As the speed of the rotor increases (in the direction of the rotating field) not only does the frequency of the rotor e.m.f. diminish, but also the magnitude of the e.m.f. diminishes, this, like the frequency, being directly proportional to the difference in the speeds of the rotor and the field.

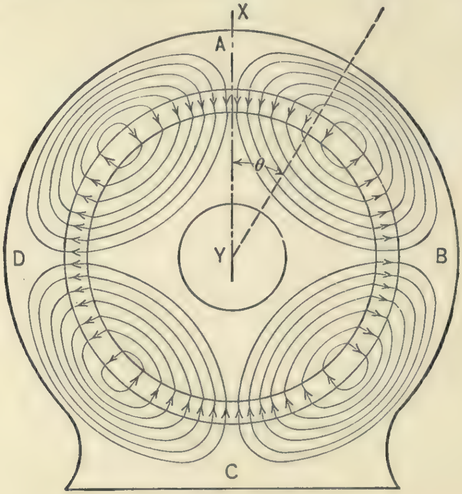


FIG. 26.

The ordinary small induction motor has a squirrel-cage winding, a set of bars imbedded in the rotor slots with short-circuiting rings connecting all the bars together at their ends. Evidently, at a certain instant, the various bars of the rotor will have different e.m.f.'s induced in them, because they are lying in different density of field. A crude idea of this voltage distribution is shown in Fig. 27, where the length of the various arrows indicates the relative magnitude of the e.m.f. induced in the different conductors. The conductors marked *A* in Fig. 27 would correspond to those in the densest fields in Fig. 26. As the magnetic field rotates faster than the rotor, the inductors of the rotor which have the maximum e.m.f. in them continually move forward over the surface of the rotor, so that in any one rotor conductor, the induced e.m.f. goes through alternating values, the number of cycles being fixed by the relative speeds of the rotor and rotating field.

As the rotor circuits have reactance as well as resistance, the current which flows in the rotor bars will not be in phase with the rotor e.m.f., but behind it by an angle depending upon the ratio of the reactance to the resistance. As the e.m.f. in each conductor is a sine wave, the current in any conductor will be a sine wave, and the current will be distributed among the rotor bars in just the same manner as is the voltage. An attempt to picture this is shown in Fig. 28.

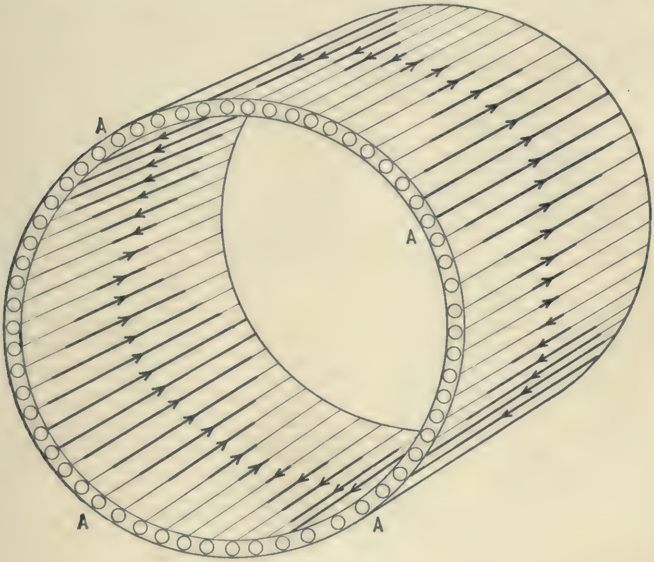


Fig. 27.

The dashed lines give the current distribution at a certain instant, and the full lines shown the voltages in the different conductors for the same instant. It is seen that the position of maximum current is not the same as that of maximum voltage, in fact, the conductor having maximum current is behind that having maximum voltage by an electrical angle ϕ, fixed by $\tan \phi = \frac{\text{reactance of rotor circuits}}{\text{resistance of rotor circuits}}$, which in the case of the four-pole motor shown is represented by a mechanical angle just half as large.

The torque exerted by the motor is due to the fundamental principle that a conductor carrying current, situated in a magnetic field, experiences a force proportional to the product of the current and field, and in a direction perpendicular to both. Now, the magnetic field has its maximum density where the rotor conductor e.m.f.'s are the greatest; hence, the conductors having the greatest rotor current are not in the fields of maximum density, which they should be to get maximum possible torque.

It will be seen by combining Figs. 26 and 28 that some of the rotor conductors carrying positive current are in negative magnetic fields; because of this effect, the net torque is less than it should be. By increasing the resistance of the rotor circuit by some scheme or other, the angle of lag of the current behind the voltage can be lessened. This angle would also be lessened if the reactance of the rotor circuit were lessened; but after the rotor is once built, this cannot be done economically. Of course, increasing the resistance of the rotor circuit will diminish the current in the circuit; but this diminution in current will not decrease the net torque as much as the decrease in angle of lag increases the torque. This is suggested in Fig. 29, where the effect of increasing the rotor circuit resistance is shown. Small increases in rotor circuit resistance do not diminish the current appreciably but they do very materially increase the cosine of the angle of lag, and the greater the cosine (for a given current) the greater the

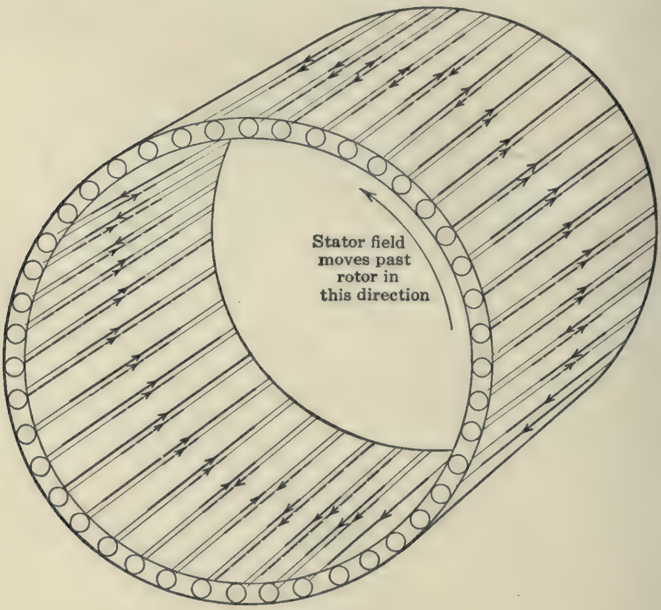


FIG. 28.

torque. It is shown in the text of Volume II, by this and other arguments, that maximum torque is exerted when the rotor circuit resistance has been increased to equal the rotor circuit reactance, a condition which exists at point *A* in Fig. 29.

The induction motor, especially at standstill, is seen to be nothing but a transformer with short-circuited secondary. The current taken from the line when the stator is connected must thus be very large, much larger than full-load current. The case is not quite as bad as it would be with the ordinary constant-potential transformer, because the magnetic leakage between the stator and rotor circuits is much greater than it is between the primary and secondary of an ordinary transformer. This magnetic leakage (large because of the air gap between rotor and stator) helps to limit the current taken by the motor at starting. But even so, the starting current of a squirrel-cage induction motor may be five times full-load current.

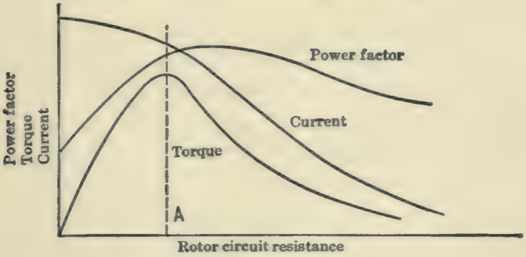


FIG. 29.

Just as the current in the primary of a transformer can be diminished by increasing the resistance in the secondary circuit, so in the induction motor, by increasing the resistance in the rotor the starting current is diminished. Thus not only is it advantageous to increase the rotor resistance in order to increase the starting torque, as explained above, but the added advantage of decreased starting current, at higher power factor, is obtained.

Most induction motors are therefore fitted with wound rotors (see Section 270 of Volume II) so that extra resistance can be inserted into the rotor circuit when starting; enough resistance is added to make the rotor circuit resistance equal to the rotor circuit reactance, thus obtaining for starting the maximum torque of which the motor is capable. As the rotor speeds up, the frequency of the currents flowing in the rotor is decreased, and so the reactance is decreased proportionately; to maintain the equality between the rotor resistance and reactance, therefore, the resistance is gradually cut out as the motor speeds up, and is entirely removed as the motor approaches normal speed. If left in for normal operation, the speed regulation of the motor would be bad and the efficiency low; evidently, whatever electrical power is used in the rotor circuit in heating the added resistance must subtract proportionately from the efficiency of the motor.

The direction of rotation of the motor may be reversed by merely interchanging any two of the leads going to the motor, in case it is three-phase, or by interchanging the leads of one phase if it is a two-phase motor.

After all the extra resistance has been removed from the rotor circuit, the induction motor will run with about the same speed regulation as a shunt-wound continuous-current motor of the same size. With no load, the motor will run within a few revolutions per minute of synchronous speed; at full load, the slip (decrease in speed from synchronous speed) may be as much as 10 per cent. If load is continually added, by Prony brake, for example, the decrease in speed will become proportionally greater until, when the torque demanded by the load reaches perhaps 150 per cent of the rated value for the motor, the speed suddenly falls off and the motor stops completely, the current taken by the stator increasing very rapidly as the motor slows down. This point of maximum torque, beyond which the motor becomes inoperative, is called the *pull-out torque*. After the load has been increased beyond the pull-out point and the motor slows down, the load must be at once removed, or the motor disconnected from the power supply; otherwise the motor will very quickly be damaged by overheating of the insulation.

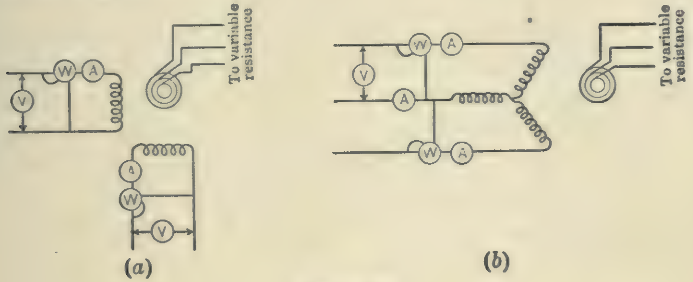
Procedure.—With a polyphase, wound-rotor, induction motor, three load runs are to be made, one with the rotor short-circuited and two with added resistance in the rotor circuit. For a two-phase motor, make connections as in Fig. 30*a*, and for a three-phase as in Fig. 30*b*. Instead of using two or more voltmeters to read voltage of lines, only one is really necessary, this being transferred as required.

In measuring three-phase power with two wattmeters, as in Fig. 30*b*, one wattmeter will read negatively if the power factor of the motor is less than 0.5, which it is almost sure to be at light load. Under this condition the connection of the potential circuit of the wattmeter is to be reversed and the reading called negative. The motor input is then the difference of the two wattmeter readings, instead of the arithmetical sum.

Calculate full-load torque (if Prony brake is to be used for loading) and take readings of input, current, voltage, torque, and speed for about eight values of torque between zero load and 50 per cent overload.

Keep the impressed voltage and frequency constant during the runs. In case a generator is used for load, its losses must be known for a definite field current and through a certain speed range. Knowing the losses of the generator, its required output to load the motor to $\frac{1}{4}$ load, $\frac{1}{2}$ load, etc., can be readily determined.

Make the load run first with rotor short-circuited, and start at full load; the power factor for full load will be much higher than 0.5, so that both wattmeters (three-phase assumed) will read on the scale if they are properly connected. Hence, at full load, connect the wattmeters so that both of them read on the scale and call them both positive. Then if one of them goes to zero and reverses as the load is decreased, this meter must have its potential leads reversed and the reading then called negative.



(*a*) (*b*)

Fig. 30.

Perform two other load runs with resistance added in the rotor circuit; the larger resistance should be sufficient to cut down the speed of the motor to 50 per cent of its rated value when full-load torque is being exerted by the motor (that is, when full-load current is flowing). The other value of resistance should be sufficient to give half this drop in speed.

Try the effect on direction of rotation of reversing any two of the leads for a three-phase motor, or either phase of a two-phase motor. Using brake for load (generator is not generally satisfactory for this test) with normal impressed voltage, find the pull-out torque with various values of resistance added in the rotor circuit, noting the speed at which pull-out occurs.

In getting starting characteristics, make connections as shown in Fig. 31, having a suitable ammeter inserted in two lines of the rotor. Lock the rotor (by brake) and apply half-rated voltage; it is necessary to carry out this test at half voltage, as otherwise the motor would be overheated. Take readings of torque, rotor current and stator input for several values of external resistance in the rotor circuit. Determine the values of resistance, if they are not marked. Measure also (by c.c.) the resistance of the rotor windings. Assuming the rotor to be Y-connected, the resistance per phase will be one-half the resistance measured between any pair of rings.

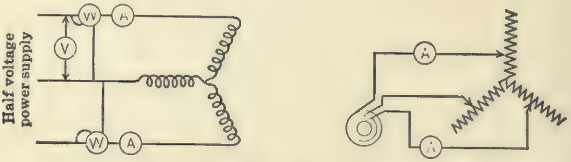


FIG. 31.

Curves.—Plot curves of speed, power factor, torque, and efficiency, for the three-load runs, using output as abscissa.

Plot on another sheet curves of starting torque, stator current, rotor current, and stator power factor as the rotor circuit resistance was varied, using total resistance (per phase) for abscissa. Of course, these curves cannot be continued to a resistance lower than that of the rotor itself. Extrapolated, however, the starting torque should be zero when the rotor circuit has zero resistance.

Plot a curve of pull-out speed against rotor circuit resistance, using rotor circuit resistance as abscissa.

Questions.—

1. What would be the approximate no-load and full-load speeds of a 24-pole, 60-cycle motor, and of an 8-pole, 25-cycle motor?

2. Could an induction motor be obtained from a manufacturing company which would give a no-load speed of 1000 r.p.m. when operated on a 60-cycle line? How many poles would it have?

3. If a 60-cycle, 6-pole motor is made to give a full-load speed of 450 r.p.m. by adding resistance in the rotor circuit, about what efficiency might it be expected to have?

4. If a three-phase motor has one fuse blown in its lines, will it continue to operate? How would it behave when next an attempt was made to start the motor?

5. If the brushes on the rings of a slip-ring rotor induction motor are lifted, how much torque will the motor exert? Why?

6. A 60-cycle motor has a slip at full load of 10 per cent; the self-induction of the rotor per phase is 0.001 henry. The resistance of the rotor per phase is 0.05 ohm. What is the impedance of the rotor, per phase, at full load?

7. In the above motor, how much resistance should be added (per phase) in the rotor circuit, to give maximum torque at starting? To give maximum torque at half speed?

VII. THE SYNCHRONOUS MOTOR

Object.—The study of the action of a polyphase synchronous motor; variation of armature current with field current for fixed load; variation in phase position of its rotor as load is varied.

Theory Involved.—If a load is essentially constant, demands constant speed and requires but infrequent starting and stopping, the synchronous motor offers the most advantageous drive. Electrically driven merchant ships, pumps, blowers, etc., are being equipped with synchronous motors in increasing numbers.

Essentially the synchronous motor is nothing but an alternating-current generator (having salient, separately excited poles in its field structure), to which electrical power is being *supplied.* If several alternators are operating in parallel in a power house, or on a common bus bar, and the steam supply is shut off from the driver of one of them, this machine will not stop, as might be imagined; it will not even decrease its speed. Instead it will continue to run at the same speed it had when acting as an alternator, but suitably connected wattmeters will show that electrical power is being *supplied* to the machine in question; it is running as a synchronous motor, giving off enough mechanical power to run its driver.

From outward appearance, an alternator and a synchronous motor cannot be distinguished; actually, the armature of the motor is wound with somewhat more reactance than would be used in an equivalent alternator, and the equipment of damping grids in the pole faces, with interconnecting straps between pole faces, is likely to be more complete in the motor than in the generator.

As a synchronous motor is inherently not self-starting, some other action than that involved in its synchronous operation must be called upon to bring it up to synchronous speed. The purely synchronous motor action gives no net torque at all until the motor reaches synchronous speed; as much average torque is developed in one direction as in the other. One method which might be used requires a small induction motor for starting the synchronous motor. The induction motor, mounted directly upon the shaft of the synchronous motor, has a capacity about 5 per cent that of the synchronous motor, just enough to supply the no-load losses of the synchronous motor.

It is designed with one pair of poles less than the synchronous motor, and of such a rotor resistance that when it is loaded to the extent of the no-load losses of the synchronous motor, it runs at a speed which is synchronous speed for the synchronous motor. Such a scheme, however, requires that the load to which the synchronous motor is normally connected be removed during the starting period, say, by clutch or similar means.

The method in practically universal use to-day makes the synchronous motor itself act like an induction motor during most of the starting period, then calls into play another action, different from that of the induction motor, to pull the machine into synchronous speed.

As was analyzed in Chapter VI, Volume II, the armature reaction of a polyphase winding, supplied with polyphase currents, is such that the combined action of the various phases gives a magnetomotive force (which produces a flux if permitted to do so) which has a space distribution essentially sinusoidal, and which is constant in magnitude and rotates at a definite speed around the armature structure. This is indicated in Fig. 32, which represents the stationary armature of a four-pole synchronous motor. The length and direction of the arrows show the direction and intensity of the magnetomotive force set up by the armature coils. The flux which is produced by the magnetomotive force rotates at a speed fixed by the frequency of the power supply, being 1800 r.p.m. for a four-pole motor supplied with 60-cycle power. Although the m.m.f. is distributed sinusoidally in space, as indicated in Fig. 32, the resultant flux will not have this distribution because of the effect of the salient poles of the field structure. The actual flux

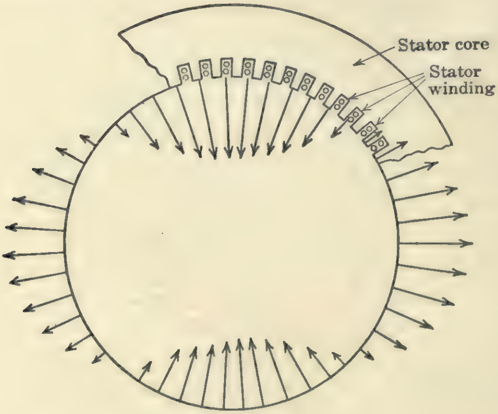


Fig. 32.

distribution due to the m.m.f. of Fig. 32 is shown in Fig. 33; this flux, it is to be noted, is not due to any ampere-turns on the field poles, but is set up by the armature ampere-turns.

Now, the pole faces of a synchronous motor are fitted with heavy brass or copper damping grids, and brass or copper links are frequently carried from the grid in one pole face to those in the adjacent poles. This interconnected set of grids is essentially the same as the squirrel-cage winding of the rotor of an induction motor. As the flux, pictured in Fig. 33, rotates, the field structure being stationary, it will evidently cut the conductors of this squirrel-cage winding, and torque will be developed exactly as though the motor was a real induction motor. It is to be noted, however, that whereas the flux of an induction motor remains constant in magnitude as it rotates, this is not the fact with the synchronous motor, because of the non-uniform magnetic structure of the rotor. When the armature m.m.f. lines up with the poles (as supposed in Fig. 33) the flux produced by the armature ampere-turns is a maximum; it falls off quite appreciably from this value when the positions of maximum armature m.m.f. line up with the interpolar space of the field structure.

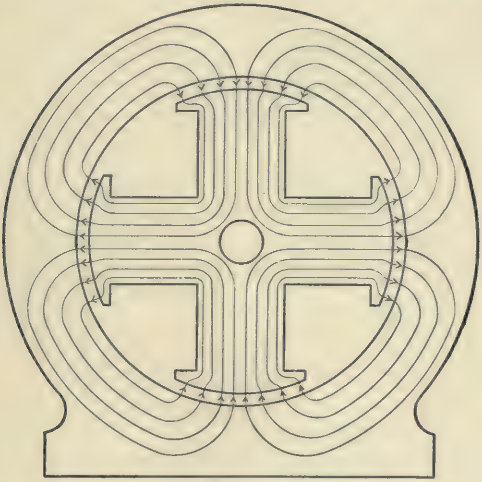


Fig. 33.

The effect of the currents induced in a squirrel-cage winding is to give a torque which tends to make the winding follow the field, and so the field structure of the synchronous motor (which during this starting process has no current in its field coils) starts to turn in the same direction as the armature m.m.f. As the flux through the magnetic circuit of the field is alternating during this starting process, it is well to have the poles laminated, so that the flux through the poles can readily reverse without causing too much heating in the poles themselves.

This induction-motor action of the synchronous motor during starting will give sufficient torque to rapidly accelerate the motor, provided it is unloaded; in special design this induction-motor action has been made sufficient actually to start the motor when loaded, but the starting current drawn from the line in such a case is much more than rated full-load current of the motor, and gives disturbances in the line voltage when the synchronous motor is started.

In any case, the current taken by the synchronous motor when starting is heavy, so much so that the starting period must be made short or the armature winding will overheat. To keep the starting current reasonably low, the motor is generally connected to its power supply line through a *compensator* (a polyphase auto-transformer), connected to a two-throw multipole switch, as shown in Fig. 34. By throwing the switch to the left, half, or two-thirds, voltage is impressed on the armature winding of the synchronous motor until it reaches nearly synchronous speed. The switch is then thrown to the right and the motor will pull into synchronism in a few seconds.

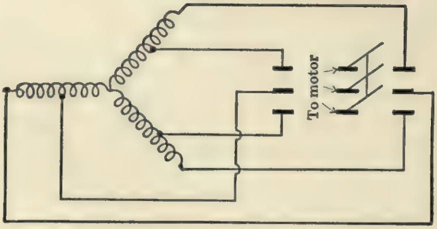
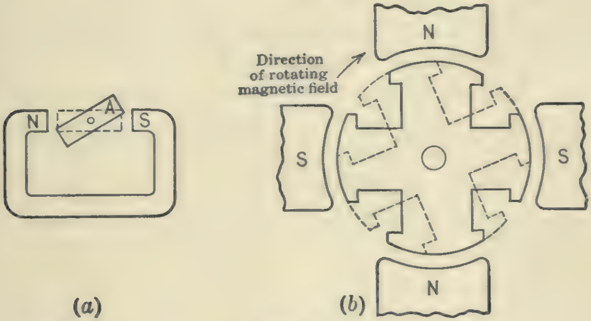


Fig. 34.

It is evident that the synchronous motor, acting as an induction motor, could never pull itself into synchronous speed; to give any torque, the induction-motor action requires that the motor be turning at a lower speed than the field. It is evident, then, that some additional action is necessary to make the synchronous motor pull into synchronous speed. The extra action arises from the salient pole structure, giving non-uniform magnetic reluctances in different portions of the field with respect to the armature m.m.f.'s.

This extra action is really that of a synchronous motor, but does not appear to be so because the field structure is apparently not magnetized; there is no field current. It is, however, magnetized by the armature ampere-turns. Consider a horseshoe-shaped magnet, as shown in Fig. 35*a*, having a bar of soft iron, *A*, pivoted so as to be rotatable. In the position shown by the full lines, *A* will experience a turning moment in clockwise direction tending to pull it into line with the magnetic field, as shown by the dotted lines. Likewise, the four-pole synchronous motor field structure placed in the magnetic field of the armature structure of Fig. 33 will experience torque, as suggested in Fig. 35*b*. The magnetic poles of the armature ampere-turns are here shown as actual salient poles to make the picture more vivid; the action is the same, even though the magnetic structure of the real armature is a uniform one. If the four-pole structure of the synchronous motor finds itself in the position indicated by the dashed lines of Fig. 35*b*, it will experience a torque tending to pull it in a clockwise direction to line up with the magnetic field. This action, it will be noticed, is entirely independent of any current which may be present in the damping grids.



(*a*) (*b*)

FIG. 35.

Now, the currents in the damping grids bring the field structure almost to synchronous speed, as in the ordinary induction motor; then at a certain instant, the field structure, turning at less than synchronous speed, occupies, with respect to the armature field, the position shown in the dashed lines of Fig. 35*b*, and so experiences the force mentioned above, which, it will be noticed, tends to still further accelerate the field structure. These two combined actions get the field structure rotating at a speed so close to synchronous speed that finally the force described in connection with Fig. 35 actually pulls the field structure into line with the armature m.m.f.'s and holds it there, that is, holds the field structure at synchronous speed. It really is now a synchronous motor, having its field poles magnetized with a definite polarity, the magnetizing force, however, coming from the armature winding instead of from the continuous current in its field windings.

During this starting period it is evident that the flux through the magnetic structure of the field is an alternating one, and as such it must induce a voltage in the field coils. Because of the large number of turns in the ordinary field coils, this voltage is high and may break down the insulation of the field windings to the field frame. To prevent this, it is sometimes suggested that the field coils be short-circuited during the starting period, but this may result in currents in the field coils of such magnitude and phase as to reduce the starting torque which the damping grids are generating. To limit this action and to sometimes increase the starting torque, some synchronous motors are equipped with an outside resistor which is connected across the field terminals during the starting interval; this allows some current to flow, so that the voltage induced in the field coils is kept reasonably low. In a certain small 10-kv.a., 110-volt synchronous motor, the voltage induced in the field coils during the starting period is 1900 volts. The Standardization Rules of the A. I. E. E. recognize this induction by stating that for synchronous motors to be started as induction motors, with open-circuited fields, the insulation test of the field should not be less than 5000 volts.

After the machine pulls into synchronous speed, the current taken by the armature drops; it may have been two to three times full-load value during the starting interval and will perhaps fall to about full-load current when it pulls into synchronous speed. The field structure is now magnetized with a definite polarity by the armature ampere-turns, just as though a certain amount of current were flowing through the field windings. The next step in putting the motor into operation is to excite the field by continuous current. It may be that the current magnetizes the field poles in the opposite direction to that in which they are already magnetized by the armature m.m.f.'s; in that case the armature current *will increase* as the field current is increased, instead of decreasing as it should. In this case the machine will generally slip one pole and the field current will now be in the right direction to help the armature magnetize the field with the result that as the field current is increased, the armature current will drop until when normal field current is flowing the armature current will have decreased to about 10 per cent of its full-load rated value.

Load may now be put on the motor and it will continue to run at synchronous speed, shifting its phase (with respect to the phase of the impressed e.m.f.) sufficiently to draw from the line a current suitable for the load being supplied. In general, to maintain the power factor of the motor at unity as the load is increased, a slight increase in field current will be required as load is increased.

In the laboratory it frequently happens that the synchronous motor has, directly connected to it, a continuous-current generator which is to be used for putting load on the synchronous motor. In such a case, the continuous-current machine offers an easy method of connecting the synchronous motor to the line.

The c.c. machine is used as a motor, and the synchronous machine is made to run at synchronous speed, its voltage being adjusted to equal the line voltage. Then, with three lamps connected at *a*, *b*, *c*, as in Fig. 36, it is possible to tell when the voltage of the motor (now running as a generator) is opposite to the line voltage; when such is the case the switch may be closed and the motor is ready to take load. The three lamps should each have a voltage rating the same as the voltage of the line; they will wax and wane in brilliancy if the frequency of the motor and the line are not quite the same, and in the middle of a dark period the switch may be closed. It may happen that the three lamps do not flicker together, but follow one another in their cycle of brilliancy. If such is the case the switch must not be closed; the motor is rotating (electrically) in the wrong direction. By reversing the connections of any two of the lines to the switch, either on the motor side or the line side, this incorrect condition will be remedied and the lamps will flicker together, and the switch may be closed in the middle of a dark period. (For further notes on synchronizing, see Section 195, Volume II.)

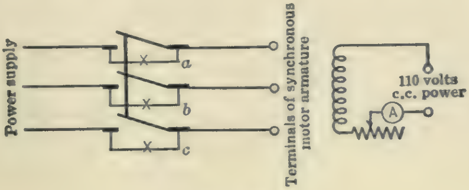


FIG. 36.

If the load on the synchronous motor is kept constant and the field current is varied, the so-called " V " curves, or phase characteristics, of the motor will be obtained. The explanation of these curves is given in the text in Sections 290–292, Volume II. It will be noticed, in the laboratory, that in getting the " V " curves for the no-load condition, the minimum value of armature current cannot be brought to zero, as it should be theoretically; in some cases the minimum current will not fall to less than 10–20 per cent of full-load current. This difference between theory and practice is due to the different forms of e.m.f. waves of the line and motor; a comparatively small dissimilarity will result in quite a large complex upper-harmonic current, even with normal field current in the motor and no load.

The shift in phase position of the synchronous motor is measured by the scheme shown in Fig. 37; it utilizes two rotating contacts (similar to that used in Exp. I) in series with each other. Disc *A* is mounted on the shaft of the power supply alternator, if this is large compared with the synchronous motor being tested; otherwise it is mounted on the shaft of a small auxiliary synchronous motor whose only function is to drive the contact disc. The other contact disc is mounted on the shaft of the synchronous motor. The two discs are connected in series through a condenser (of about one microfarad) to a 110-volt continuous-current line. If both strips in the rotating discs make contact with their brushes at the same instant, the voltmeter will deflect; otherwise not. The brush of disc *B* (on the motor) is mounted on a graduated arc so that it may be rotated 360 electrical degrees and its position accurately noted at any time.

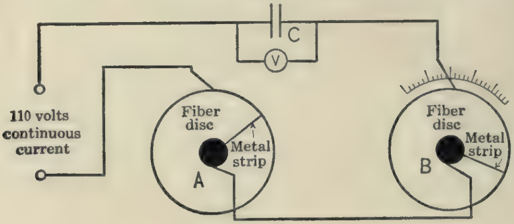


FIG. 37.

When the motor has been synchronized, and its field current adjusted to give minimum armature current with no load on the motor, the brush of disc *B* is moved over the arc until a maximum reading is obtained on the voltmeter *V*, and this position of brush *B* becomes the " zero phase " position of the motor. The c.e.m.f. of the motor is now just opposite in phase to that of the line. For any other loading or excitation of the synchronous motor, the brush of disc *B* is again moved to give maximum reading on the voltmeter, and the difference between this and the " zero phase " shows the number of degrees the motor has advanced or retarded its phase to accommmodate itself to the new conditions put upon it.

In case the full-load current of the motor forms an appreciable load for the alternator supplying the power for the synchronous motor, this scheme (if disc *A* is on the power supply alternator) will give phase shifts considerably greater than the true ones. The armature reaction of an alternator results in a sidewise shift in its field, as explained in

Section 173, Volume II. With this twist in the position of its field, the voltage of the alternator changes its phase with respect to the fixed brush of disc *A*; it moves ahead of the position indicated by the brush of disc *A* by several degrees, the amount depending upon the load the alternator is carrying. And even in the case of the no-load run on the synchronous motor, if the current required by the motor forms an appreciable *IZ* drop in the armature of the generator, the terminal voltage of the generator (which is what is impressed on the armature of the synchronous motor) will shift its phase considerably, even though the position of the field is not twisted at all.

To overcome these difficulties (which cannot readily be corrected for), disc *A* may be carried on the shaft of a small unloaded synchronous motor; the brush of disc *A* will then always bear a fixed position relative to the e.m.f. impressed on the test synchronous motor, and the shift of the brush on disc *B* will really measure the shift of phase position of the test motor with respect to its impressed voltage.

As shown in the theory of Section 294, Volume II, there will be a small shift in phase position of the synchronous motor as the field excitation is varied, load being fixed; in getting the no-load " V " curves, for example, it will be found that for under-excitation the synchronous motor advances its phase and for over-excitation it retards its phase. In getting the load run, with conditions changed to maintain unity power factor as load changes, it will be found that the phase position of the motor falls back practically proportionally to the load, being perhaps 15 electrical degrees from no load to full load.

Procedure.—Arrange the field circuit of the synchronous motor for potentiometer connection to the c.c. power supply, the connection being as in Fig. 38. By one of the two schemes outlined above (or preferably both), synchronize the motor, and if necessary readjust its field current to make the armature current a minimum. In case a c.c. machine has been used to synchronize the motor, it should be disconnected from its power supply and its field circuit opened, before carrying out the adjustment for minimum armature current at no load. Running free, with no field current, its losses will be very small, so that the synchronous motor may be regarded as unloaded.

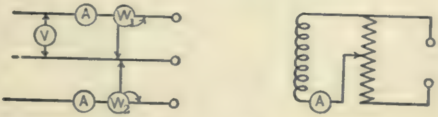


FIG. 38.

Find the phase position of the armature by means of the two rotating discs (Fig. 37); note how to change the readings of the scale on the arc of disc B into electrical degrees. Also note which way the scale reads with respect to motor rotation, so as to be able to tell from the data whether the synchronous motor advanced or retarded its phase.

With no load on the motor and its field current set at such a value as to give minimum armature current, the power factor will be close to unity and the two wattmeters of Fig. 38 should read positively and alike. If one of them has to have its potential leads reversed during the progress of the test, note that its readings must be called negative. Take especial care on this point, as each of the wattmeters (in turn) will require this reversal of its potential connections.

Next, decrease the field current (motor still unloaded) to such a value that the armature current will rise to 25 per cent greater than its rated value, and note this value of field current. Then increase the field current above its normal value until the over-excitation is sufficient to give again 25 per cent greater than rated armature current, and note this value of field current. Now get a series of readings (about eleven) between these two limits of field current, reading watts, volts, armature amperes, field amperes, and phase position. The watts input should be essentially constant (rising somewhat at the higher armature currents) during this run, and there should be only a very few degrees phase shift.

Now bring the field current back near its normal value and put sufficient load on the motor to bring the armature current (with field current set to give minimum armature current) to one-half its rated value. It is to be noted that minimum armature current, for a given load, occurs with that adjustment which makes the two wattmeters read alike. Now with the load left at this value, get a series of readings of power, volts, armature amperes, field amperes, and phase position, as the field current is changed both above and below normal, about as in the previous run. The limits of field current (to cause armature current to rise to 25 per cent overload) in this case will not be so far apart, however, as they were for the unloaded motor.

Carry out a similar run for such a load on the synchronous motor that the armature current is full-load rated value when at its minimum value. It is likely that in this run it will not be necessary to reverse either of the wattmeter potential leads, as the power factor is not likely to decrease below 50 per cent for any value of field current permissible.

Now return to the no-load condition and adjust for unity (maximum) power factor, by making the two wattmeters read alike. Note power input, armature and field amperes, voltage and phase position. Put about $\frac{1}{8}$ load on the motor, if necessary, readjust the field current to make the two wattmeters again read alike, and get the same readings as before. Carry out similar readings for a series of loads up to 25 per cent overload.

Having finished these runs, study more in detail the starting of a synchronous motor, if time permits. In the case of compensator starting, get the approximate curve of starting current *versus* speed and time, so that a curve of starting current and speed can be plotted with time as the other variable. In the case of synchronizing lamps, try the effect of reversing any two of the power supply lines, on the flashing of the lamps.

If the apparatus permits, increase the load to the pull-out point of the motor, having in the circuit ammeters and wattmeters of range greater than the setting of the circuit breakers which are necessarily in the supply lines, when this test is carried out. Read the power, phase position, and current input when pull-out occurs.

Curves.—On one sheet plot the *V*-curves, using field current as abscissae, and as ordinates, armature current, watts input, power factor, and phase position. On a second sheet, plot a curve of watts output *versus* phase position from the results of the last run, using phase position as abscissae. In case sufficient data are not available to get power output, use power input (instead of output) for the curve.

Questions.—

1. What is the frequency of the e.m.f. induced in the field circuit of a synchronous motor being started as an induction motor?

2. If a small induction motor is used to bring the synchronous motor up to speed for synchronizing, why must it have one pair of poles less than the synchronous motor?

3. Comparing induction motors to synchronous motors for ship propulsion, it is found that a saving of 15 per cent in generator and cable expense is possible if synchronous motors are used. Why?

4. A three-phase synchronous motor is drawing 125 amperes from a 2300-volt line at a power factor of 0.78 leading. How much power is being supplied to the motor? How much is the reactive current taken from the line?

5. A synchronous condenser (see Section 296, Volume II) is to be used on a 6600-volt line supplying an induction motor load, taking 65 amperes at a power factor of 0.72. Assuming it takes no power to run the condenser, what must be its rating if it is to just compensate the lagging current taken by the induction motors?

6. What must be the rating of the above condenser if it is to increase the line power factor from 0.72 to 0.95?

7. What must be the input rating of a synchronous motor which is to bring the above line power factor from 0.72 to 0.95 and at the same time deliver 200 horsepower, its efficiency being 85 per cent?

8. What is meant by the hunting of a synchronous motor, and how may it be lessened?

VIII. THE SYNCHRONOUS CONVERTER

Object.—Study of the synchronous converter; factors affecting its voltage ratio; determination of its operating characteristics.

Theory Involved.—In many of the larger cities a part of the distribution system is laid out for continuous-current service; motors and other apparatus already installed make it inadvisable to try to change the system over to the more modern and flexible alternating-current system. For an indefinite time, these customers will require a continuous current from the supply.

The heart of any electric transportation scheme is the motor; the series motor is much better suited for traction purposes than any other type, because of its high starting torque and the inherent change in speed with change in demands of the load. The power supplied to the trolley or third rails of electrified roads thus must be such that a series motor can be used to advantage. Whereas the series alternating-current motor is possible, it is inherently so much more expensive to build and maintain, and its operating characteristics are so much poorer than those of the continuous-current series motor, that unless special conditions exist, the continuous-current motor is used. Probably 95 per cent or more of the traction motors in service to-day are continuous-current motors.

For charging storage batteries, electro-plating, and various other processes, c.c. power is necessary, a.c. power being out of the question.

Now, in spite of these demands for c.c. power, it is not economical to generate and transmit c.c. power; the required investment for copper, and the poor regulation obtained, make the generation and distribution of c.c. power over any but very short distances impossible. Modern power stations always generate a.c. power, and it is transmitted as such; some translating device must then be interposed between this a.c. transmission system and the c.c. distribution system, which will change the high-voltage power of the a.c. system to a low-voltage c.c. supply. There are available mercury arcs, or vacuum tube rectifiers, for small amounts of power, and for larger amounts, motor-generator units or synchronous converters. To study the latter is the object of this experiment.

The synchronous converter (or rotary converter, as it is frequently called) is essentially a revolving-armature synchronous motor, which has had a commutator connected to its winding, and is equipped with suitable brushes, as would be required for any corresponding c.c. machine. Supposing a Δ-connected armature for a three-phase synchronous motor, this winding may be represented by a closed-mesh winding which, for a two-pole machine, is tapped at three equidistant points of the mesh for making connections to the slip rings with which the revolving armature must be equipped. Such a winding is indicated in Fig. 39, the three points where the slip-ring taps are taken from the winding being indicated at *A*, *B*, and *C*. Now, such a winding may be fitted with a commutator having the same number of bars as there are coils in the winding, and this is indicated in Fig. 39. Brushes resting on the commutator (in the proper interpolar space) will have a continuous voltage impressed on them as the winding is revolved in the magnetic field. It makes no difference what rotates the armature; the e.m.f. is generated in the winding just the same, and the brushes will show it. Hence, if the armature runs as a synchronous motor by having suitable polyphase power applied to the slip rings to which taps *A*, *B*, and *C* are connected (the slip rings are put on the end of the armature opposite to that on which the commutator is fitted), the brushes on the commutator will show a continuous voltage, just the same as though the armature were being revolved by a belt and pulley or a steam engine.

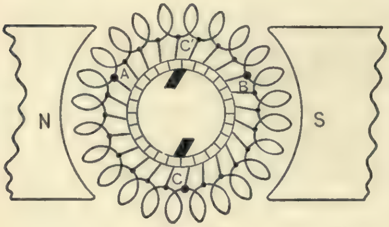


FIG. 39.

The current which flows in the various coils of the armature winding will, quite evidently, not be of simple form. Running into all coils on the a.c. end is alternating current, of essentially sinusoidal form; running off from the brushes is a continuous current, which means that in the coils themselves there is flowing an alternating current of rectangular shape. The form of current flowing into a coil from the a.c. end is shown in Fig. 40*a*, and that current in the coil due to the continuous current being drawn from the brushes on the commutator is shown in Fig. 40*b*. The actual current in a coil will be the difference between

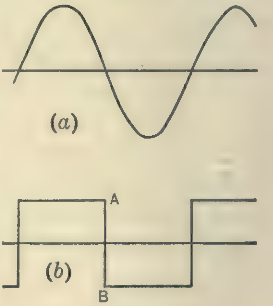


FIG. 40.

these two currents, evidently a complex form. Moreover, the a.c. current input will have the same phase for all coils in series between adjacent taps (e.g., between *A* and *B* of Fig. 39), whereas the rectangular current in the coil demanded by the c.c. load will reverse from positive to negative at a different time for every coil between these same taps. The reversal of current from *A* to *B* of Fig. 39 takes place as the coil in question passes under a brush on the commutator; evidently all of the coils commutate one after the other, not synchronously.

The actual current forms are made up of displaced sections of sine waves, as was shown in Section 311, Volume II; some actual oscillograms of such currents are shown in Fig. 41.

A given closed winding (like that of Fig. 39) will show a maximum voltage between a.c. taps if these are placed 180 degrees apart, as, for example, C–C' of Fig. 39. Moreover, the maximum instantaneous value of this voltage will occur when the taps C–C' are in the interpolar space, as shown in Fig. 39. Now, here the a.c. taps connect to practically the same points of the winding as do the brushes on the commutator, so we deduce the relation that the maximum instantaneous value of the alternating voltage between 180-degree taps is the same as the continuous voltage at the brushes. This gives us the relation that the effective voltage between 180-degree taps is 0.707 of the voltage at the commutator, if a sine wave is impressed. If the voltage impressed is not a pure sine wave, the ratio of a.c. to c.c. voltage will differ somewhat from this theoretical value. As the voltage between 120-degree taps of the winding is equal to the 180-degree voltage multiplied by sin 60 degrees (see Section 308, Volume II), the effective voltage between the three-phase taps, *A*, *B*, and *C*, will be 0.612 of the continuous voltage. Of course, if the alternating voltage is not sinusoidal, this ratio will be somewhat different. If the wave is more pointed than a pure sine wave, the ratio of a.c. voltage will be less than 0.612 of the continuous voltage; and if flat-topped, somewhat more than this theoretical value. In practice, the ratio may differ as much as 5 per cent from the theoretical value.

This ratio of alternating to continuous voltage must necessarily be independent of either the speed at which the armature is turning, or the value of the field current of the machine; in the above deduction these were not even considered. The relation is fixed only by the spacing of the a.c. taps; it is 0.707 for 180-degree taps and 0.612 for 120-degree taps. For a six-phase converter the voltage between adjacent taps is only 0.35 of the continuous voltage. As a six-phase converter is always supplied with power from a three-phase power supply by suitable transformer connections, it may be thought of as

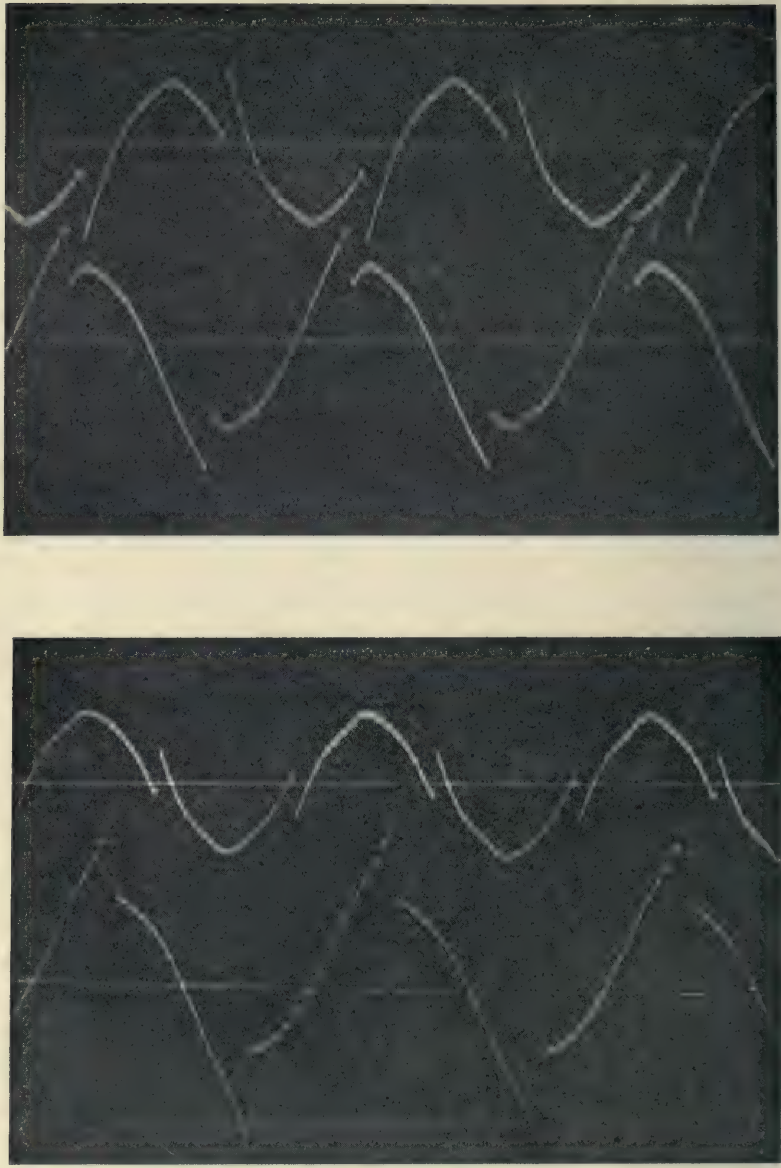


Fig. 41.

a double three-phase power supply, the voltage ratio then being the same as for a three-phase converter.

The synchronous converter may be started by either of the two methods outlined for starting synchronous motors, i.e., by a separate small induction motor, or by the induction motor method using the damping grids. In addition, there is the possibility of starting the converter from the continuous-current end of the machine, using it as a shunt motor. For converters used to supply lighting systems, this latter scheme is generally used; the c.c. voltage is steady and the converter speed may be carefully adjusted for synchronizing by means of the field rheostat. For railway work this method is not so good because of the large and rapid fluctuations in the voltage of the c.c. network; several cars or trains starting at once may suddenly lower the voltage 10 per cent or more, and this fluctuation will make the speed of the converter (being run as a shunt motor) correspondingly vary; under these conditions, the synchronizing process would be difficult to carry out. For railway systems, therefore, the converter is generally started by small induction motors, or as an induction motor by the help of its damping grids. This induction motor method of starting is not advisable on a lighting system, because the large starting current required will lower the voltage of the a.c. supply system and so give a corresponding drop in the voltage of the c.c. distribution system (supposedly already alive and supplied by other converters) with corresponding flickering of the lamps.

In case the induction motor method is used for starting the converter, all of the brushes on the commutator, except one pair of special high-resistance material, are lifted off the commutator during the starting period. Owing to action described in Section 321, Volume II, vicious sparking takes place at the brushes on the commutator during the starting period, and this sparking, if allowed to recur every time the converter is started, will seriously impair the commutator. A lever properly fitted to the various brush studs allows the brushes to be lifted clear of the commutator while the machine is being started.

The power factor of the converter on the a.c. end can be altered at will by suitable adjustment of the field current, just as was done with the synchronous motor; but in practice the power factor is always held close to unity, as otherwise excessive heating of certain of the armature coils results, thereby reducing the capacity of the converter.

With normal field current (that which makes the power factor of the a.c. input unity), there is practically no armature reaction in the converter; that due to the synchronous motor input is nearly balanced and neutralized by that due to the continuous-current output. As more load is taken off the commutator end, the a.c. end automatically draws more power from the a.c. line, just as does the primary of a transformer when the secondary load is increased. The phase position of the converter stays practically constant as load is varied and does not change 15–20 degrees as is the case with the synchronous motor.

Procedure.—Two runs are to be made with the converter running from the c.c. end, the first to determine the voltage ratio of the converter and its possible variation, and the second to get the operating characteristics of the converter when it is operating from the a.c. end, as it is normally designed to do. For making these two runs, it is convenient to make connections as in Fig. 42; the converter there shown is designed for 110 volts on the a.c. end, so that to properly synchronize it the voltage required on the commutator end is 110 ÷ 0.612 = 181 volts. A 220-volt line with a rheostat in series is therefore suitable for connection to the commutator end for starting and synchronizing.

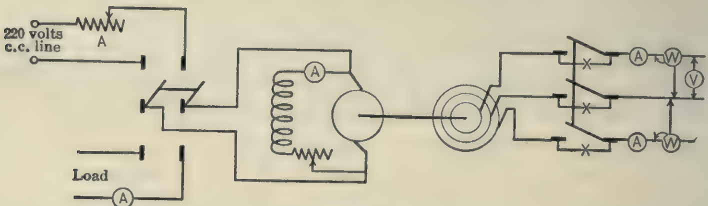


Fig. 42.

It is to be noticed that the converter connected in this fashion will probably not start by itself, even though the rheostat should be reduced until full-load current is flowing in the stationary converter armature. The reason is the lack of field current; with the armature stationary, its winding forms a short circuit for its field current, so that the field coils get so little current that practically no starting torque is developed. If the rheostat resistance is decreased until a reasonable current is flowing in the converter armature, however, and then the armature is turned by hand (in the right direction) it will start to run and come up to proper speed.

If the converter is started in this fashion, and synchronizing lamps are used, as shown in Fig. 42, trouble may be experienced from incorrect phase rotation, just as was the case with the synchronous motor; if all lamps do not flicker together, reverse two leads of the a.c. power supply.

In case the converter is started from the a.c. end with field circuit open, trouble may be experienced as a result of improper polarity. (as was shown to be possible in Section 320, Volume II), or with reversed field connection.

If, when the field connection is made, the armature current increases, this shows that the field is improperly connected to the commutator end of the machine. The field connection must be reversed and then when the field circuit is closed, the current taken by the armature from the a.c. line will decrease, as it should.

If the converter comes into synchronism with reversed polarity to the c.c. line to which it is to be ultimately connected (as indicated by the switchboard voltmeter), it is customary to reverse the field connections to the commutator. This causes the converter armature to slip back one pole; in this new position the polarity of the converter is correct. However, if the field is left reversed, the converter will continue slipping, one pole at a time. Therefore, as soon as the polarity is correct, the field must be quickly changed to the position of proper field connection.

In testing for voltage ratio, keep the machine running from the c.c. end, but do not synchronize it with the a.c. line. Keep the impressed armature voltage constant and vary the speed through as wide a range as possible (having due care for excessive speed) by changing the field strength; read the voltage on the commutator and that on the slip rings. Then make another run, keeping the speed constant with various voltages impressed on the commutator, keeping the speed constant in this case by suitable changes in the field current. Read continuous voltage and alternating voltage as before.

In taking the load run, the machine is first to be synchronized with the a.c. line. After the starting rheostat (*A* in Fig. 42) has been regulated so that the voltage at the slip rings is the same as that of the a.c. supply, vary the speed by field rheostat, until the synchronizing lamps indicate approximate synchronism, and close the synchronizing switch in the middle of a dark period. When synchronized, the double-pole, double-throw switch in the c.c. power supply circuit is to be opened and thrown the other way, to permit loading by lamp banks or other suitable means.

Adjust the field current so that at no load the alternating-current supply is a minimum, and leave the field rheostat at this adjustment during the rest of the load run. Put on load in about eight steps from zero to 150 per cent overload, keeping the voltage impressed on the slip rings and the frequency constant. Read input and output, field current, and phase position, the phase position being obtained as was done for the synchronous motor test.

Curves.—On one sheet, plot the voltage ratios as obtained in the first two runs, using ratios as ordinates, with speed and impressed voltages as abscissae.

On a second curve sheet, plot curves obtained from the load run, using c.c. load amperes as abscissae and c.c. voltage, efficiency, power factor, and phase position as ordinates.

Questions.—

1. What voltage must be impressed on the a.c. end of a three-phase converter if there is to be 600 volts on the c.c. end?

2. In starting the converter as an induction motor, why is one pair of brushes left on the commutator?

3. In the operation of a converter substation, does the operator have to consider the possibility of the armature current increasing as field current is increased, after synchronizing?

4. What is the operator to do if the converter c.c. voltmeter shows reversed polarity after the converter pulls into synchronism?

5. A three-phase converter is rated as 600-650 volts on the commutator end; through what range must the impressed voltage vary as load is increased?

6. What current would be drawn from the alternating-current line by a three-phase railway converter, which is rated as 300 k.w., 600 volts, if it has an efficiency of 95 per cent, power factor being unity?

7. Explain why the voltage on the commutator end of a converter, operating normally from the a.c. end, does not rise as the field current is increased.

8. Why is it inadvisable to use a synchronous converter to increase the power factor of a line, by overexciting its field?

IX. THE PARALLEL OPERATION OF ALTERNATORS

Object.—To study the operation of alternators in parallel; what determines their load division and the effect of improper field adjustments; effect of speed-load characteristics of their prime movers.

Theory Involved.—The modern power station has an installed generator capacity of several hundred thousand kilowatts; as even the largest generators of to-day have an output of not more than about 50,000 k.w., it is evident that several of them must be operated in conjunction to furnish the station load. The several alternators cannot be operated in series, for two reasons. They are electrically unstable, in that if they are synchronized in such phase that their respective voltages add together to give a bus-bar voltage twice that of one machine, any load furnished by the machines will tend to pull them out of the proper phase position and reduce the bus-bar voltage to zero. To prevent this the generators would have to be coupled together mechanically, a rather difficult undertaking. The second and more important reason for not operating alternators in series comes from the demands of the distribution service; no matter how much load is called for, the voltage of the distribution system must stay constant, otherwise lamps, household utensils, etc., would burn out.

If the alternators furnishing power to the bus are all connected in parallel, the bus-bar voltage will be the same no matter how many machines are operating, namely, the voltage of any one of the alternators. As more alternators are connected in parallel, the voltage of the station will remain essentially constant and the possible current output will go up proportionally with the number of machines put into service. This arrangement fits in exactly with the demands of the distribution system and is always used.

It becomes important, then, to study the operation of alternators in parallel, to discover how the load can be transferred from one machine to another, what effect the governor action of the prime movers has upon the operation of stations, what the effect of varying the field excitation of the various alternators has on the load division and possible output of the station, etc.

It quite frequently happens that two alternators, each of which is a satisfactory machine by itself, will not operate in parallel because of violent hunting. Sometimes, in the laboratory, it is impossible to hold two machines in parallel; after they are properly synchronized the armature current rises in pulsations corresponding to the period of hunting, continually increasing until the circuit breakers or other protective apparatus blow. This hunting is much more likely to occur if the prime mover is one giving a pulsating torque; for example, hunting is more likely to occur if the prime mover is a reciprocating steam engine, or worse, a gas engine, than if a steam turbine or electric motor is used for the prime mover. The hunting is frequently due to improper speed-load characteristics of the prime mover; one in which the speed stays constant or increases with load is very unstable for the driver of an alternator operating in parallel with others.

Alternators which are to operate in parallel with others should always be equipped with heavy damping grids; not only should the pole faces be equipped with liberally proportioned grids, but heavy connecting straps should connect together the end bars of the various pole-face grids.

An alternator to be operated in parallel with others must first be synchronized with the bus bar; this requires that the magnitude of the generated voltage of the incoming machine be adjusted to equal the bus-bar voltage, and that the frequencies be essentially the same. By means of synchronizing lamps or synchroscope, the instant is noted when the machine voltage is exactly opposite to the bus-bar voltage and the synchronizing switch is closed. Of course, care must be taken, in synchronizing, that the phase rotation of the incoming machine is the same as that of the bus bars; in a station this point never arises after the machines are once installed, but in the laboratory improper phase rotation is just as likely to occur as proper phase rotation. When three lamps are used for synchronizing, as in Fig. 43, the lamps will go bright and dark together if the proper phase rotation is had; if the lamps flicker in sequence, as *a*—*b*—*c*, the phase rotation of the machine and bus bar is opposite and the synchronizing switch must not be closed. Reverse any two of the leads, either on the bus side of the switch or the machine side; this will reverse the phase rotation of the side changed and the lamps will flicker simultaneously.

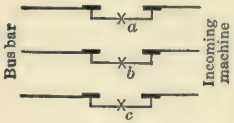


FIG. 43.

After a machine is synchronized with the bus bars it will take no load, neither will any appreciable current flow between it and the bus bars. It would seem natural that to make it take load we should increase the field current of the recently connected machine, just as we should do if it were a c.c. generator; if this is tried, it will be seen that the ammeters in the lines of the test machine will go up proportionately to the increase in field current, but the wattmeters, properly connected as in Fig. 44 to indicate its power output, will continue to indicate zero or may more likely deflect in such a way as to indicate power flowing *into* the test machine, rather than flowing *out*. Moreover, it should be found that if the field current is decreased (from the normal value, or the value it had when synchronizing) instead of increased, the same result occurs; the wattmeters indicate practically no input or output, but again the ammeters show a current which increases as the field current is changed from its normal value.

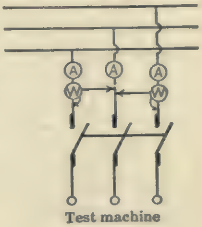
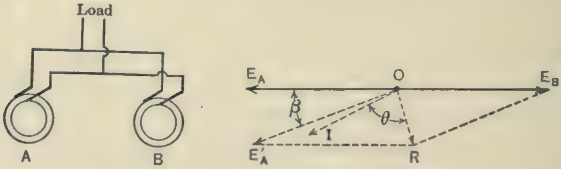


Fig. 44.

If now the field current is brought back to its normal value (the value it had just before closing the synchronizing switch) the ammeters and wattmeters will both read zero, or nearly so. In general, the ammeters will not read exactly zero, no matter what changes are brought about in excitation; this is due to the dissimilarity of the e.m.f. wave forms of the bus bars and the incoming machine. Unless these two voltages are of exactly the same form, a complex current will flow between the incoming machine and the bus bars, even when the voltage of the incoming machine just before synchronizing is adjusted to exactly the same effective value (read on a voltmeter) as that of the bus-bar voltage. On certain machines experimented with, this complex circulating current could not be reduced below 10 per cent of the rated full-load current of the machine.

To make the incoming machine take load it is necessary to increase the torque of the prime mover in some way; in case a steam engine or turbine is used for driving the alternator, its steam supply must be increased, and if a shunt motor is used, its field current must be decreased. As the torque of the prime mover is increased, it tries to increase the speed of the alternator and does so to a slight extent for a small fraction of time. As the alternator advances in phase (with respect to the bus-bar voltage) the alternator will assume load, the amount of load it assumes being nearly proportional to the angle of phase advance. It will be noticed in this case that as the torque of the prime mover is increased not only does the indication of the ammeters increase (as it did when the field current was changed from normal), but the wattmeters indicate power output for the alternator. In Fig. 45 the action is indicated for a single-phase alternator; for a three-phase alternator, the same diagram would hold good if the voltages used were considered as the voltages per Y-phase. In Fig. 45*a*, machine *B* represents all the machines already operating on the bus bars of the station, and machine A is the one which has just been synchronized; the diagram of Fig. 45*b* shows the voltage, E_A, of machine A, to be just equal and opposite to E_B, the voltage of the bus bars, the condition which was obtained before closing the synchronizing switch. As the resultant voltage is zero, no current flows from the machine into the bus bars.

If now, due to the increased force exerted by the prime mover, machine A pulls ahead (with respect to machine B) so that its voltage is properly shown at E'_A (again using the voltage E_B for reference), there is the resultant voltage OR acting in the local circuit. If we suppose the joint impedance of the armatures of the machines already operating on the bus to be negligible compared with the impedance of the test machine, which would be the case, for example, if nine machines were already running on the bus bars when the incoming machine was switched on, then all the voltage OR must be used up as IZ drop in the armature of the incoming machine. Knowing the impedance of this armature, we can calculate the magnitude and phase of the current which must flow in the test machine; it is shown in Fig. 45*b* as OI. This current is seen to be practically in phase with the voltage E'_A of the incoming machine and so represents a load on it. By slightly increasing the excitation of machine A the current OI may be shifted in phase to come directly in phase with E'_A if desired.



(*a*) Fig. 45. (*b*)

By inspection of Fig. 45*b*, it will be seen that for small values of phase shift, β, the value of OR, and hence of OI, will be directly proportional to β itself. Thus the load on the incoming machine is directly proportional to the magnitude of the angle by which it pulls ahead of the position it had when synchronized.

In case there are only two alternators operating in parallel, the adjustment carried out on the test machine will have a large effect on the bus-bar voltage. In the case considered above, if the excitation of the test machine was altered, the bus-bar voltage did not appreciably change, as the other nine machines were acting to keep it constant. But if there is only one other machine operating on the bus bars, increasing the field current of the test machine will naturally increase the bus-bar voltage. Also, a given increase in torque of the prime mover of the incoming machine will not result in as much load increase, because, as the phase of the incoming machine advances, the other machine tends to follow it, so that a given change in torque does not give as great a change in the angle of phase advance (β in Fig. 45*b*). Furthermore, the frequency of the power supplied to the bus bars will now fluctuate to a much greater extent than before, as the torque of the prime mover is adjusted up and down.

Let us suppose that two alternators of about the same rating are in parallel and supplying a load which is sufficient to load them both to their rating. The proper division of this load, we assume, has been brought about by adjustments of the torques of their drivers. Now, what will happen if the load is gradually reduced? Will the alternators continue to divide the load proportionally to their ratings? Such is far from the fact; the manner in which the load will divide as it is gradually reduced (nothing else being changed) depends entirely upon the speed-load curves of the drivers, and practically not at all on the characteristics of the alternators themselves.

The alternator connected to that prime mover which has the poorer speed regulation will take a larger and larger fraction of the load as this is reduced. As the load on this prime mover is decreased, it tries to speed up more than does the other with closer speed regulation. Pulling ahead makes its alternator take an ever-increasing share of the load. Thus, if the two prime movers have speed-load curves as shown at *A* and *B*, Fig. 46, the effects to be expected are as follows: If the two machines are synchronized, with no load on the bus bars, and then load is put on, machine *B* will take by far the greater share of the load. If at full load, the machines are so adjusted that they divide the load equally, then as load is reduced, machine *A* will take a continually increasing fraction of the load until it is carrying all the load and in addition is running the alternator to which driver *B* is connected as a synchronous motor. Of course, with the changes in load, the bus-bar voltage and frequency will change, both of them increasing as the load on the bus bars is lessened.

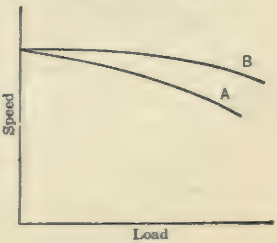


FIG. 46

Procedure.—Make connections as in Fig. 47, with machine *A* running and carrying about half load (non-inductive). In these first tests, it is best to have the voltage of alternator *A* controlled by a voltage regulator to keep it constant. Synchronize machine *B* with the bus bars and read field current, watts output, armature current, voltage and phase position (to be obtained as in Exp. VII). Leave the field current fixed at this value, and increase the torque of the prime mover of machine *B* in such steps as will produce changes in the armature current of machine *B* of about 25 per cent rating. Take the readings up to about 50 per cent overload if possible, reading for each step armature current, voltage, and watts of machine *B*, as well as the phase position of *B*.

Now, reduce the torque of the prime mover of machine *B* until the power output is zero. Decrease the field current until full-load armature current is flowing, and read power, armature current, field current, and phase position. Increase the field current above normal until full-load current is again flowing, and get the same readings as before. Get a similar set of readings for about ten other values of field current between the two limits.

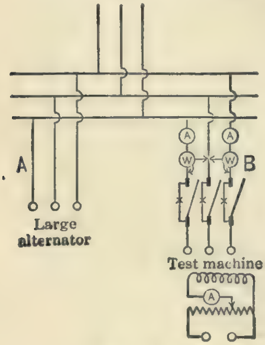


FIG. 47.

Using two alternators of about the same rating to supply a resistive load equal to the sum of their ratings, and having an ammeter in the load circuit, divide this load proportionately to their ratings. Reduce the reactive circulating current to as near zero as feasible, by making the sum of the currents flowing in each alternator equal to the current delivered to the load. That the circulating current has been reduced to a minimum may also be noted from the wattmeter readings of either machine; when these are reading equal and both positive, the circulating current is a minimum, (true only for a resistive load).

Get the frequency and line voltage at approximately their correct values. Read frequency, bus-bar voltage, phase position of one machine with respect to the other, armature current, and power of each alternator. Now decrease the load in about six equal steps, changing nothing but the load. Read frequency, bus-bar voltage, load current, power, and current of each machine, and phase position. Take one set of readings with zero load.

Note.—It is not easy to get exactly the full-load condition called for in this test, namely, rated frequency and voltage, full-load on each machine, and no reactive current. Get full-load current on each machine and no reactive current, then get the voltage and frequency as near the rated value as the time available warrants.

Curves.—On one curve sheet, plot (from the results of the first run) variation of power load on machine *B* against phase position of its armature, using phase position as abscissae. Calculate the reactive current circulating between the machines for each reading, and plot the curve also against phase position. From the results of the second run, plot power output of the alternator, armature current, reactive current, and phase position, against the field current of machine *B* as abscissae. From the third run, plot the variation of bus-bar voltage, frequency, reactive circulating current, power of each machine, phase position of the machine observed, all against load current as abscissae.

Questions.—

1. An eight-pole alternator is to be synchronized with a 60-cycle bus. At what speed must it run?

2. If machine *A* is generating 60 cycles, and before synchronizing the lamps flicker twice per second, how fast is machine *B* running, if it has eight poles?

3. Why should the field current of the several alternators in a power station be so adjusted as to make the reactive circulating current as near zero as possible?

4. Suppose that two similar three-phase machines are operating in parallel, each having a rating of 1000 kv.-a., 2300 volts. If there is a circulating reactive current of 180 amperes, how many kilowatts of power can they safely furnish to a resistive load?

5. From the standpoint of armature reaction, why does the generated voltage of machine *A* increase when the field current of machine *B* is increased, the two machines being in parallel?

6. What will happen if one attempts to operate two alternators in parallel on a load, alternator *A* being driven by a shunt motor and alternator *B* by a differentially compounded motor?

7. Why are gas engines poor prime movers for alternators operating in parallel?

8. Would a Y-connected alternator operate satisfactorily in parallel with a Δ-connected alternator?

X. THE SINGLE-PHASE MOTOR

Object.—Study of the starting and running characteristics of various types of single-phase motors: the single-phase induction motor; the repulsion-induction motor; the single-phase series motor.

Theory Involved.—Alternating-current power is generally distributed to the customers' premises as single-phase. If the customer uses a great deal of power, all three phases will be brought to his premises; but the small customer has to get along with single-phase power. There is then evidently need for a satisfactory single-phase motor, especially in small sizes, say, 5 horsepower and less.

The single-phase induction motor is entirely satisfactory for those loads requiring essentially constant speed, provided some means is available for starting it. The single-phase induction motor *per se* has no starting torque at all. It may be started as a split-phase motor (see Section 336, Volume II), but a more satisfactory solution is to start the motor as a repulsion motor.

As outlined in Section 348, Volume II, the armature of such a motor has a winding and commutator practically the same as those of a c.c. motor. Bearing on the commutator are brushes, just as is the case with the c.c. motor, but in the repulsion motor these brushes are short-circuited, that is, two sets of brushes spaced 180 degrees on the commutator are connected directly together. Furthermore, they are arranged so that they can readily be shifted from their normal position by several degrees. In Fig. 48 is conventionally represented the field and armature of a repulsion motor; a ring winding is shown on the armature for simplicity of drawing, where actually a drum winding is used. If there were any current in such an armature, completing its path through the short-circuited brushes, the winding would carry positive current on one side of the armature at a certain instant and negative current on the other. So far as magnetic action and torque are concerned, therefore, the distributed winding may be replaced with sufficient accuracy by a single turn, the two sides of which are indicated

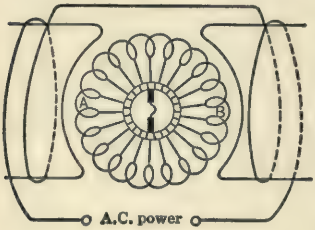


Fig. 48.

at *A* and *B*. The current in the single turn would be many times as great as that in the actual armature, to make up for the change from many turns to only one turn. The position of this equivalent coil, it will be noticed, is at right angles to the line of the short-circuited brushes. Hence, by moving the short-circuited brushes we move the position of the equivalent short-circuited coil. The diagram of Fig. 48 may thus be replaced by the simpler one given in Fig. 49, where the three positions of the equivalent coil correspond to the action of the actual armature for these positions of the brushes. With the equivalent coil in position *B–B′*, there will be no current in the coil at all; whatever current circulates in it must be due to transformer action with the field, and as, in the position *B–B′*, none of the field flux links the armature coil, no current flows in it, and so evidently no torque can be exerted by the rotor. If the brushes of the actual motor were turned 90 electrical degrees, the equivalent coil would go to position *A–A′*. Here the coil corresponds to the short-circuited secondary of a transformer and so will have a large current circulating in it; a large current will also flow in the field circuit, just as it would do in the case of a transformer (the field circuit of Fig. 49 corresponds to the primary circuit of a transformer). Although a large current will flow in coil *A–A′*, the armature could not exert torque, as the coil sides do not lie in the field flux.

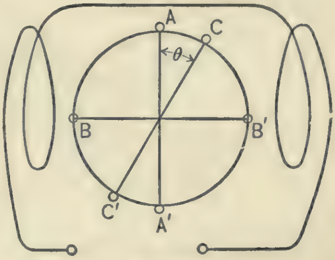


Fig. 49.

If the equivalent coil occupies some such position as *C–C′*, Fig. 49, there will still be a large current flowing (not as large as for position *A–A′*), and as the coil sides will lie in a magnetic field, torque will be exerted. As this torque will tend to make the coil pull into position *B–B′*, clockwise torque will be exerted. But rotation of the armature due to the torque does not change the position of the equivalent coil, as this is fixed by the position of the short-circuited brushes, which, of course, remain fixed as the armature rotates.

From what has been said above, it appears that, as the brushes are shifted, the current taken, and the torque exerted, by the motor will go through wide changes. These are shown by the curves of Fig. 50. In position *C–C′* the current is nearly equal to its maximum value, which occurs for position *A–A′*, and high torque is exerted. The angle ϕ in the ordinary motor is about 15 degrees. It will be seen from Fig. 50 that the torque may be reversed by moving the brushes past the position corresponding to the equivalent coil position A–A'. As the single-phase motor runs equally well in either direction after it gets up to speed, this adjustment of the brushes furnishes a convenient means of reversing the direction of rotation of the motor.

The repulsion motor has many of the characteristics of the series motor, notably no fixed upper speed limit; as load is removed the speed continually mounts. As the motor, operating as a repulsion motor, approaches synchronous speed, the torque it would develop as an induction motor continually increases, about as shown in Fig. 51. When the motor gets to some such speed as 1700 r.p.m. (for a four-pole, 60-cycle motor), its torque as an induction motor is high, and here a centrifugal device clamps a short-circuiting ring on the commutator of the motor, which has up to this time been a repulsion motor. This changes the armature to a completely short-circuited winding, the equivalent of a squirrel-cage rotor. After this, the motor operates satisfactorily as a single-phase motor. If for any reason the motor should slow down much below 1700 r.p.m., the torque would rapidly decrease and the centrifugal device would again operate, changing the motor back to a repulsion motor.

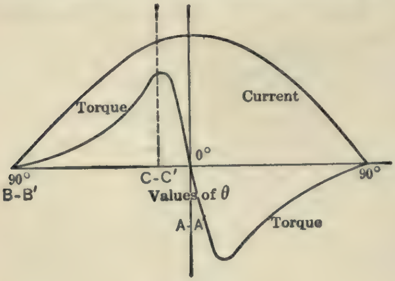


FIG. 50.

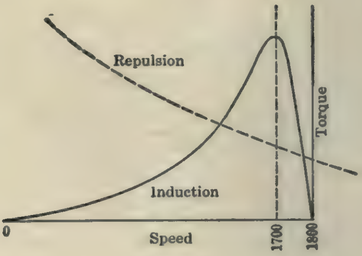


FIG. 51.

The repulsion-induction motor has a wound armature and commutator, similar to those of the repulsion motor described above; there are at least two sets of brushes on the commutator, however, and these are not rotatable, neither is there a centrifugal device to short-circuit the armature at speeds near the synchronous value. The brushes of the *RI* motor (as it is called) remain permanently on the commutator, and they are fixed in place before leaving the factory and should not be changed thereafter. The general idea of this type of motor is indicated in Fig. 52, which supposes a two-pole motor. One set of

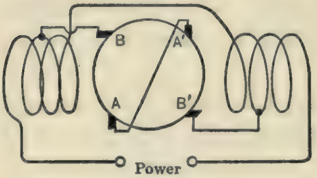


FIG. 52.

brushes, $A-A'$, is short-circuited as for the repulsion motor; the other set, $B-B'$, is connected to the stator winding in the ordinary type of motor, at such points of the winding that the power factor of the motor will generally be near unity throughout a large part of its operating range. This connection of the rotor circuit to the stator gives what is called the compensation feature of the motor, and the motor is styled the compensated *RI* motor.

As the repulsion principle is continually present in this type of motor, it is not strange that it runs above synchronous speed, which is generally the case. A four-pole, 60-cycle compensated *RI* motor, for example, might have a speed of 1750 at full load and 1850 at no load; its power factor will generally be well over 90 per cent from $\frac{1}{4}$ load to any reasonable overload.

The single-phase series motor is electrically similar to the c.c. series motor, but there are certain changes in construction required by the fact that the flux throughout the whole magnetic circuit is alternating; this requires that the entire magnetic circuit, field as well as armature core, be made of laminated iron. Furthermore, because of the fact that hysteresis and eddy-current losses occur in the field structure, the flux density in this part cannot be as high as it is in a good c.c. series motor, resulting in a larger motor than is required for continuous current. Not many field turns can be used in the a.c. series motor, because the self-induction of the field coils prevents an appreciable current from flowing through the motor. To obtain a reasonably high-power factor in this type of a.c. motor, the flux set up by the armature ampere-turns must be neutralized as completely as possible; this is done by a compensating winding wound in the pole faces, this winding being connected in series with the field coils and armature.

Since a transformer effect from the alternating field flux produces heavy currents in the coils, which are instantaneously short-circuited by the brushes, it is necessary to increase the resistance of the armature coils. So-called resistance leads are therefore used in the entire armature winding (Section 346, Volume II).

Even after all precautions have been observed in the design and construction of the single-phase series motor, its operation is much inferior to what it will do when connected to a continuous-current line. In any but the very small motors used for household purposes, the series motor is always built for 25 cycles, never 60 cycles. The performance of a motor which on 25 cycles is reasonably satisfactory, is unexpectedly poor when tried on 60 cycles. In the small sizes, the single-phase series motor is used extensively for fans, vacuum cleaners, etc.; and in the larger sizes, it is used on some few railroads which have been electrified with single-phase alternating current. The a.c. series motor will operate very well on continuous current, whereas the c.c. series motor will not operate at all on alternating current.

Procedure.—Load the single-phase induction motor by a Prony brake and get all of its characteristics, operating as an induction motor; these characteristics are speed, current, efficiency, torque, and power factor. Of course, the impressed voltage and frequency should be kept constant at their rated values. Obtain the pull-out torque.

To get the characteristics of the motor operating on the repulsion principle, it is necessary to impress half voltage, as otherwise the motor would overheat. With half voltage impressed, and normal frequency, get the input, output, speed, power factor, torque, etc., for speeds below that at which the centrifugal device operates.

With half voltage impressed and the rotor clamped, get a set of readings similar to those of Fig. 50, reading torque and current for about six positions on either side of that giving zero torque.

With a compensated repulsion-induction motor loaded by Prony brake, get data for curves of speed, input, current, power factor, torque, and efficiency, from no load to the maximum safe load on the motor.

With rotor locked, get data for a curve showing variation of starting torque with impressed voltage. Having the armature clamped, read torque, current, and voltage for a series of voltage values up to that which gives maximum safe current.

With the single-phase series motor normally connected, get the operating characteristics when operating at normal voltage and frequency; precaution should be taken to prevent overspeeding.

Get the same characteristics for the motor when operating on a line of much higher frequency than that for which it was designed; say, if the motor is a 25-cycle machine, operate it on 60 cycles.

Get the same characteristics of the motor when operated on a continuous-current line of the same voltage as that at which the motor is rated.

Curves.—On separate sheets, draw curves of running and starting characteristics of the different motors tested; in the case of ordinary running characteristics, use horsepower output as abscissae. For starting characteristics, use starting current or setting of the brushes as abscissae. For the repulsion motor run, plot speeds as abscissae with current and torque as ordinates.

In the case of the half-voltage runs, multiply currents by two and torques by four to get the values which would have been obtained if normal voltage had been used.

Questions.—

1. Why should the torque of a repulsion motor vary with the square of the impressed voltage?

2. What would be likely to happen if a 60-cycle induction motor, starting as a repulsion motor, should be connected to a 25-cycle line instead, and why?

3. With full-load current of 50 amperes flowing through a series alternating-current 110-volt, 60-cycle motor, the power factor is 0.7. About how much current will it draw from a 110-volt, 60-cycle line, if clamped so that it cannot rotate?

4. For a given current and line voltage, why is the output of a series motor so much greater on a continuous-current line than on an alternating-current line?

5. What would be the probable safe output of a 10-h.p., 220-volt, 60-cycle induction motor if run on a 110-volt, 25-cycle line?

6. From the standpoint of flux interlinkages, what is the fundamental principle involved in the operation of the repulsion type of motor?

XI. THE WATT-HOUR METER

Object.—A study of the operation and adjustment of the single-phase, alternating-current watt-hour meter.

Theory Involved.—The watt-hour meter indicates the amount of energy a customer uses; as it is the determining factor on which the revenue of the power companies depends, it is very essential that it be kept accurate in its indications. This is an especially important item from the company's viewpoint, because practically all neglected meters tend to run slow.

A watt-hour meter is essentially a small motor, so constructed that the speed of rotation is directly proportional to the power passing through it; as the meter is put in series with the customer's load, its reading, fixed by the time integral of the power supply, indicates the energy supplied. The watt-hour meter, as ordinarily designed and built, develops a torque proportional to the power supplied; in the case of a single-phase, alternating-current meter, this torque is therefore proportional to $EI \cos \phi$, that is, the watts supplied to the customer. The motor will accelerate because of this torque and will continue to accelerate until some opposing torque balances this torque, making it cease to accelerate. The balancing torque always comes from the braking action of a copper or aluminum disc, carried on the meter shaft, running between the poles of a permanent magnet. The torque developed in the electromagnetic brake is directly proportional to the speed, hence the speed of the motor must be directly proportional to the torque developed by the power supplied through the meter. We have, evidently

$$\text{Accelerating torque} = KEI \cos \phi$$

$$\text{Retarding torque} = K'N$$

where N is the speed.

As the meter will speed up until these two torques balance, we have

$$N = K''EI \cos \phi.$$

As the number of revolutions executed is proportional to the speed × time, and as the energy supplied is determined by power × time, it follows that the total number of revolutions is proportional to the amount of energy supplied.

Although the mercury-motor meter is used to a slight extent to measure alternating-current energy, practically all a.c. watt-hour meters are of the induction type. These are generally single-phase, two-wire, but may be built for single-phase, three-wire, two-phase, or three-phase circuits. We shall examine the single-phase two-wire meter, the kind used in practically every small customer's premises.

In Fig. 53 are shown in elevation the essential parts of a single-phase induction watt-hour meter. An irregularly shaped magnetic circuit is built up of laminations, so formed that the three projections, *F*, *G*, and *H*, constitute three poles, the faces of which are parallel, with sufficient mechanical clearance to permit the aluminum disc, *D*, to turn freely in the interpolar space.

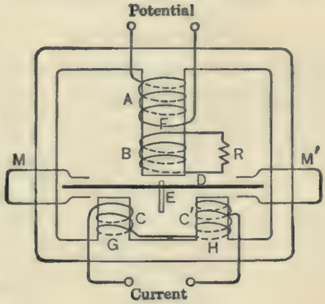


Fig. 53.

The upper pole piece *F* is wound with a coil *A* of many turns of fine wire; this coil *A* constitutes the *potential coil* of the meter. Mounted on the same pole *F* is a small coil of fewer turns, short-circuited through a resistance *R*, called the *lag coil* of the meter. The two lower poles, *G* and *H*, are wound with two coils, *C–C′*, which have a few turns and which are wound with wire large enough to safely carry the current of the load to which the meter is to be connected. These two coils are wound in opposite directions, so that at any instant the two poles are of opposite polarity.

The aluminum disc *D*, carried on a vertical spindle *E* (only a small part of which is shown), is generally of corrugated aluminum, the corrugations being put in to make the disc stiff. The upper part of the spindle *E* carries a worm which engages with a gear train, which by a series of 10–1 gears, indicates on the meter dial the number of revolutions the meter has made. By a suitable ratio of gears, the revolutions of the dials may be made to indicate directly in kilowatt-hours. The lower end of the spindle *E* is fitted with a very hard, smooth steel pivot which rests on a jewel bearing, adjustable so that the clearance between the disc *D* and the pole faces may be set at its correct value. The lower bearing may also be of a ball-bearing type; in this type of lower bearing, a steel ball rolls between two cup-shaped jewels, one fixed and the other attached to the lower end of the spindle.

The disc *D* rotates between the poles of two permanent magnets *M–M′*; the fields of these magnets will, when the disc is in motion, generate eddy currents in the disc and the eddy currents will react with the fields of the magnets in such a way that the torque produced tends to stop the disc from turning.

The reason the meter disc turns when it is connected to a load may be seen when we consider the currents set up in the disc by the flux from the three poles, F, G, and H. In order that the meter may indicate accurately on loads of various power factors, it is first necessary that the flux in pole F be 90 degrees in phase behind the voltage impressed on coil A, that is, the voltage of the load to which the meter is connected. Due to the high reactance of coil A, its current will lag about 70 degrees behind the impressed voltage and, of course, the flux in pole F, if it were produced only by coil A, would therefore lag 70 degrees, instead of 90 degrees, behind the voltage impressed on A. The function of the lag coil, B, is to give an additional m.m.f. which, combined with that of coil A, will give a resultant m.m.f. in pole F which is just 90 degrees behind the voltage impressed on coil A. Figure 54 shows how this is done. The voltage impressed on coil A is shown as OE, the current in the coil is shown at I_A, about 70 degrees behind the voltage OE. We may consider that this current gives a flux which, by its rate of change through coil B, gives in this coil a voltage E_B, just 90 degrees behind the current I_A. In the circuit of coil B, then, a current I_B will flow, an angle ϕ behind the voltage E_B. The magnitude of the current I_B, as well as the angle ϕ, are controlled by the value of the resistance R (Fig. 53). The total m.m.f. acting on pole F is therefore the vector sum of those due to coils A and B; that of A is shown at OA and that of B is shown at OB, and the vector sum is shown at OC. This then is the total m.m.f. acting on pole F and gives a flux in F which is in phase with itself; the flux through F is therefore shown at ϕ_F, and this is just 90 degrees behind the voltage OE.

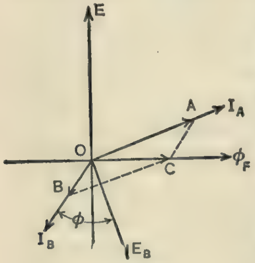


FIG. 54.

In Section 131, Volume 11, the action of the fluxes from the current and potential poles was shown to give a torque which tends to rotate the disc in a certain direction, with a torque proportional to the power flowing through the meter, and this section should be consulted before carrying out the following tests.

As long as both current and potential coils are excited, there is a force tending to make the disc turn; if either of the coils is unexcited there is no torque at all. The torque exerted will, it is almost self-evident, be proportional to the current through coils C–C' and to the voltage impressed on coil A. Furthermore, although it cannot be at once seen quantitively that the net force depends upon the power factor of the load, it may be seen that it is qualitatively true by considering the case of zero power factor. In this case the eddy currents in the disc due to the current coil would be a maximum when the flux through pole F is zero and the current in the disc due to the pole F would be zero when the flux through poles G and H was zero. Hence no net torque would be exerted and the disc would not rotate. But, of course, if the power factor of the load should be zero, the disc should not rotate because no energy is being supplied.

Just as in the case of the continuous-current watt-hour meter some special arrangement must be used to make the meter indicate accurately at light loads; the starting friction of the ordinary watt-hour meter may be such that perhaps 5 per cent of full-load current will not even start it. To overcome the starting friction there is attached to the potential pole a small copper plate which is adjustable; it is attached so that it can be swung over the face of the potential pole F to more or less cover the face. Such an arrangement is called the *shading plate*, or *starting plate*.

The general action of such a starting plate may be seen with the help of Fig. 55, which shows a plan of the face of the pole F and the starting plate B. The plate, so pivoted so as to be rotatable about some point (as A in Fig. 55), is cut by flux from the pole F; currents will therefore be induced in the plate and these currents will induce other currents in the aluminum disc directly under the plate. These currents in the aluminum disc will react with the flux from the unshaded part of pole F so as to produce a torque; the amount of this torque (which it will be seen is entirely independent of the flux from the current poles G and H) may be changed by shifting plate B to cover more or less of the face of pole F and so may be adjusted to just equalize the static friction of the meter.

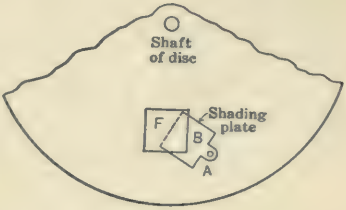


FIG. 55.

For adjusting the speed of the meter at full load, the magnets M–M' are shifted in or out from the center of the rotating disc exactly as is done for continuous-current meters.

The induction meter may be tested in either of two ways: a load may be connected through the meter and through an indicating wattmeter, which has been accurately calibrated; carrying this load through the meter for a specified time (say, one or two minutes) gives a known amount of energy through the meter and so should cause a definite number of revolutions of the meter disc. So by indicating wattmeter, stop-watch and adjustable load, the accuracy of the meter may be tested throughout its range. Another method, almost universally used, is to employ a standard rotating watt-hour meter, which has been carefully calibrated; thus neither indicating meter nor stop-watch is required. The two watt-hour meters, the test meter and the standard, are connected in series to the load; the reading of the standard is taken for a reasonable time (say, one to two minutes) and the number of revolutions of the disc of the test meter is taken for the same time. Then by direct comparison the accuracy of the meter under test is known.

It might be questioned why it is necessary to count the revolutions of the disc of the test meter; why not take the reading on the dials? The meter cannot be tested in this fashion because the lowest unit of energy that can be read on the dial is altogether too large to make an accurate test possible unless a long interval of time is used in making the test.

In a given meter the number of kilowatt-hours which pass through the meter is obtained from the number of revolutions and the so-called "disc constant," K. This disc constant (different for meters of different capacities) is equal to the number of watt-hours which pass through the meter to give one revolution of the disc. The so-called "testing constant," K_t, of the meter, is equal to the disc constant $\times$ 3600.

If an indicating wattmeter is used to test the meter in question, the calibration of the meter requires that we reduce its speed to watts; in terms of the testing constant we have

$$\text{Watts} = K_t \times \text{revolutions per second.}$$

In case the rotating standard is used, the time is taken for an exact number of revolutions of the test meter, sufficient number of revolutions being taken to make the elapsed time perhaps one or two minutes. The number of revolutions of the rotating standard for the same time is taken; the number of revolutions of this meter can be obtained accurately to a fraction of a revolution, by the properly calibrated dials with which it is furnished, hence the reason for taking a whole number of revolutions of the test meter, fractional parts of the revolutions of which could be only approximately estimated.

The rotating standard meter is adjustable to zero and is started and stopped as desired by a small snap switch which opens and closes its potential circuit.

Procedure.—Connect the circuit as shown in Fig. 56; here an indicating wattmeter is shown as the standard. The power factor is adjusted to any desired value by the combination of inductive and resistive loads, and is checked by the readings of the indicating wattmeter, voltmeter and ammeter. In case a rotating standard is used for calibrating the test meter, connect it in series with the test meter, still using the three indicating instruments to get any desired power factor, but not for calibration data.

First with non-inductive load test the accuracy of the meter received at 10, 50, 100, and 150 per cent of full-load current; take three readings for each load, taking enough revolutions of the test meter to have the elapsed time at least one minute.

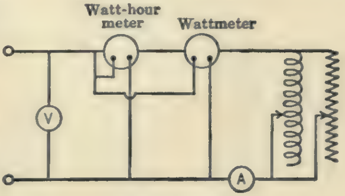


FIG. 56.

Next by means of the magnets *M–M′* adjust the meter to have less than 2 per cent error at full rated load, and then by means of the shading plate adjust the meter to have an error of less than 2 per cent with a load 10 per cent of the rated load of the meter. Having carried out these adjustments, calibrate the meter at 10, 50, 100, and 150 per cent full load current for resistive load and for loads of about 0.7 power factor.

Curves.—Draw curves of meter calibration as found and as left, for the different power factors; plot for abscissa, amperes in per cent of rated value, and as ordinates the ratio of meter watts to true watts.

Questions.—

1. How does the torque due to the shading plate vary with speed?

2. Why does the adjustment of the shading plate have a negligible effect on the accuracy of the meter at full load? What effect does the shifting of the magnets, carried out for full-load adjustments, have on the light-load speed?

3. What will be the effect of increasing temperature on the accuracy of the meter, considering separately, the current coils, potential coil, shading plate, and the rotating disc?

4. For the same diameter and weight of disc, and same braking effect, which requires stronger magnets, an aluminum disc or one made of copper?

5. What would be the effect of putting a thin sheet of copper between the rotating disc and the pole faces?

6. With a given disc, how does the braking effect vary with the magnet strength, and why?

7. What would be the probable effects of trying to operate a 110-volt, 60-cycle induction meter on a 110-volt, 25-cycle line?

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